THE DEFENSE SCIENCE BOARD REPORT ON

Technology and Innovation Enablers for Superiority in 2030

OCTOBER 2013

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REPORT OF THE DEFENSE SCIENCE BOARD

STUDY ON

Technology and Innovation Enablers for Superiority in 2030

OCTOBER 2013

Office of the Under Secretary of Defense
for Acquisition, Technology, and Logistics
Washington, D.C. 20301-3140

This report is a product of the Defense Science Board (DSB).

The DSB is a Federal Advisory Committee established to provide independent advice to the Secretary of Defense. Statements, opinions, conclusions, and recommendations in this report do not necessarily represent the official position of the Department of Defense (DoD). The Defense Science Board Study on Technology and Innovation Enablers for Superiority in 2030 completed its information-gathering in December 2012. The report was cleared for open publication by the DoD Office of Security Review on August 23, 2013.

This report is unclassified and cleared for public release.

OFFICE OF THE SECRETARY OF DEFENSE
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WASHINGTON, DC 20301–3140

DEFENSE SCIENCE BOARD

September 19, 2013

MEMORANDUM FOR UNDER SECRETARY OF DEFENSE FOR ACQUISITION, TECHNOLOGY & LOGISTICS

SUBJECT: Final Report of the Defense Science Board (DSB) Study on Technology and Innovation Enablers for Superiority in 2030

I am pleased to forward the final report of the DSB Study on Technology and Innovation Enablers for Superiority in 2030.

The study provides a framework to analyze technology and innovation enabler investments to support military capabilities required in 2030. The Department should use this framework, or substitute one of its own, to guides its investment decisions. In doing so, a key challenge will be to honestly and accurately assess current investments in the context of the framework and then curtailing investment areas which are no longer needed. In addition to identifying new investments, the framework provides an ability to monitor and react against surprise.

Transitioning technology to fielded capability will provide its own set of challenges. The robust and adaptive techniques that will support transitioning to fielded capability are likely to produce additional capability and will need to be fed back into the Department's framework.

I fully endorse all of the recommendations contained in this report and urge their careful consideration and soonest adoption.

Dr. Paul Kaminski
Chairman

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DEFENSE SCIENCE BOARD

September 13, 2013

MEMORANDUM FOR UNDER SECRETARY OF DEFENSE FOR ACQUISITION, TECHNOLOGY & LOGISTICS

Subject: Final Report of the Defense Science Board 2012 Summer Study on Technology and Innovation Enablers for Superiority in 2030

The final report of the Defense Science Board 2012 Summer Study on Technology and Innovation Enablers for Superiority in 2030 is attached. In accordance with its charter, the study reviewed emerging technologies that will enable the next generation of dominant military capabilities anticipated to be in development or fielded by 2030. The review was guided by the January 2012 military strategy guidance entitled "Sustaining U.S. Global Leadership: Priorities for 21st Century Defense."

This report recommends specific investments for the Department focused on high leverage technologies that were judged as not adequately pursued today. In the process of developing these investment recommendations, the study also identified four investment categories that complement the traditional approach of seeking increasingly technically-sophisticated, complex, and therefore expensive systems. These are recommended as a taxonomy for thinking about the Department's technology investment portfolio. The investment categories are described in this report, and are listed here:

- Coping with parity
- Achieving superiority through cost-imposing strategies
- Achieving superiority through enhancing force effectiveness
- Anticipating surprise

For each investment category, the report highlights several technology areas that were seen as under-attended, meaning they are lacking investment, effort, or focus commensurate with their potential importance to the Department. This was measured by a review of current activities inside and outside the Department of Defense rather than a thorough, detailed survey of the entire national investment portfolio. Consequently, the results of this process should not be viewed as a comprehensive list of technology investments for the Department. Rather, it is a set of priority investments that can complement, and in some cases replace, currently programmed initiatives. Given the challenging budget environment, the Department leadership will need to trade off available resources, overall strategy, and on-going activities to determine how best

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to respond to these recommendations. The report strongly recommends this investment portfolio framework be used as a tool to help make these decisions.

The study also evaluated the role of experimentation and concept demonstrations in fostering innovation and facilitating technology insertion into programs. A key recommendation in the report is to increase the use of experimentation for discovery and analysis of potential new technologies. This would replace the current Department focus on test and evaluation at developmental milestones.

Mr. James D. Shields
Co-Chairman

Dr. James A. Tegnelia
Co-Chairman

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Executive Summary

In March 2012, the Under Secretary of Defense for Acquisition, Technology, and Logistics requested that the Defense Science Board develop recommendations for technology investments that would enable the Department of Defense to maintain capability superiority in 2030. The Board assembled a study composed of national leaders in science and technology who explored required capabilities, global technology, and the principles of experimentation. This report recommends some specific investments for the Department that are focused on high-leverage technologies that the study judged are not adequately pursued today. Although the nature of the process precluded a comprehensive review of all potential technologies, the study recommends a new perspective to the Department leadership for planning its investment portfolio.

The World in 2030 and its Implications for National Security

Predicting the future is a daunting task; it is always a humbling activity to compare what was expected to what was observed over any recent 20-year period. To aid in this endeavor and to provide a context for its deliberations, the study identified some trends that can, with some confidence, be expected to influence the national security challenges that the Department will face in the 2030 timeframe.

Demographic Trends

Because all of the individuals who will be at least 20 years old in 2030 have already been born, an age demographic can be forecast with some certainty. Available data indicates that birthrates in mature and developing countries are below replacement levels. While slow population growth will relieve pressure on resources, an aging population presents new challenges. Countries where the 15- to 24-year-old age cohort represents more than 20 percent of the population—a youth bulge—have historically been less stable than countries with older populations. Some countries, including the United States, have found that immigration of younger adults mitigates lower birthrates.

The number of countries with a median age of 25 years or less is dropping from more than 80 today to less than 50 by 2030, concentrated in sub-Saharan Africa and parts of the Middle East. At the same time, Japan and many countries in Europe will have a median age over 45, a new situation in the world. These population profiles led the study to conclude that terrorist and insurgency threats will still be issues for the United States

long after the current wars are over, and that traditional U.S. allies will face increasing pressures to devote resources to aging populations, thus increasing pressures to reduce international defense efforts.

Population locations are also shifting. An increasing percentage of the world's population lives in cities and makes up a growing global middle class. Cities are frequently clustered along coastlines, making them more vulnerable to the results of climate change, including rising ocean levels and severe storms. The U.S. military must therefore be prepared to provide disaster relief and carry out humanitarian missions.

Global Technology and Equalizing Opportunity

The effect of communications and information technology that *flatten* the world has been well-documented. While the U.S. is still the world's technology leader, the gap with other nations is closing, according to such metrics as ranking of leading research universities and patents issued, among others. This trend is intensified by growth in cyber theft of intellectual property.

The shift of manufacturing capability offshore also affects U.S. technology leadership by enabling new players to learn a technology and then gain the capability to improve on it. An additional threat to defense capabilities from offshore manufacturing is the potential for compromise of the supply chain for key weapons system components.

The projected global technology landscape indicates that the U.S. should not plan to rely on unquestioned technical leadership in all fields. Further, throughout recent wars, U.S. adversaries have been able to observe both the capability of U.S. defense systems and the tactics with which they have been employed. They have seen the value of asymmetric approaches that use simple, inexpensive techniques. Future adversaries may be able to use this information, along with globally available technology, to counter longstanding U.S. advantages and may, in isolated niches, be able to achieve capability superiority.

Resource Availability and Climate Change

The rise of many developing economies and growth across Asia indicate a global shift toward emerging economic competitors. While the West, including the United States and Europe, will continue to be strong economies, China, India, and other Asian nations will grow and compete aggressively. A larger number of dynamic economies may put strains on the availability of natural resources, particularly energy. With new technology development, such as hydraulic fracturing to extract natural gas, the relative U.S. position in the energy market of 2030 may continue to improve. However, increased global resource competition may result in conflict that involves the U.S.

One of the responses to multipolar economic competition will be the increase of regional markets, partnerships, and alliances. Regional trading zones and economic alliances often come with either implicit or explicit mutual defense agreements. Shifting alliances and partnerships may complicate the diplomatic and national security calculus for the United States. Further, the nature of military competition may evolve in situations where competitors also have close economic ties or dependencies.

Defense Implications in the World of 2030

The study converged on four primary findings relative to the impact of the changing world environment:

1. Longstanding U.S. military advantages may be at risk in a world of technological parity.
2. Movement of critical manufacturing capability offshore may pose significant challenges.
3. Adversaries are likely to have niche capability superiority with the potential to disrupt both military and civilian infrastructure.
4. The U.S. should better leverage the advantages provided by the quality of the professional military.

The U.S. has long relied on technically superior equipment and systems to counter adversaries who, in many cases, had greater numbers of people in their military, or at least in the engagement, because recent combat experience has been in forward-deployed situations. Key capabilities characterized by speed, stealth, and precision have allowed largely unfettered access to the adversary's homeland where the U.S. has rapidly established air superiority. The resulting freedom of access coupled with ubiquitous observation, communications-enabled networked coordination of forces, and precision weapons, has provided the ability to conduct operations that range from massive fire power to surgical strike unprecedented in the history of warfare.

In the future, increasingly technically capable and economically strong adversaries are likely to develop counters to some or all of the foundation technologies on which the U.S. has come to rely. The advantages provided by capabilities such as GPS, internet-based network communications, satellite reconnaissance, and stealth aircraft will be diminished, and in many cases, eliminated. To maintain superiority, it will be necessary for the military to develop new capabilities or tactics, techniques, and procedures to continue to be effective when capabilities on which it has relied over the past two decades are degraded or denied.

The challenges of parity in important technologies are complicated by the movement of critical manufacturing capabilities offshore. In addition to accelerating technology transfer, offshore manufacturing of components, combined with the global sourcing of commercial technologies, puts the supply chain for key U.S. defense systems at risk. There is an increased number of opportunities for sophisticated adversaries to tamper with or compromise components before they are assembled into systems. The growing cyber security threat also means that, particularly in the case of software, complete domestic control of the design, development, and manufacturing is no longer an assurance that a system has not been compromised. Assuring the integrity of all U.S. defense systems will be an increasing challenge over time.

In an environment where the Department of Defense no longer has assured technical leadership in all relevant defense technologies, there may be niche areas where adversaries will achieve superior capability to that of the U.S. military. This situation, should it occur, is most likely in areas such as cyber, where the barriers to entry are low and capability development may not take massive financial resources. These threats may disrupt military or commercial infrastructure and could pose significant difficulties for the military to find ways to fight through or work around adversary strengths to achieve its objectives.

While the flattening technology world of 2030 may impact the relative capability advantage of U.S. equipment and systems, the study anticipates that the professionalism and training of the U.S. volunteer force will continue to provide an advantage. Identified in the study are investments that the Department should be making to maintain and leverage the quality of the U.S. soldier, sailor, airman, and marine.

Structuring the Investment Portfolio

In addition to the global trends, the Department of Defense must consider the fiscal constraints following a decade of war and the financial crisis of 2008 and 2009. While many recommendations contained in this report may be viewed as a call to spend more money, the study observed that in a projected period of flat or declining defense budgets, modifications or enhancements to established programs are many times more cost-effective than terminating old programs and creating new ones.

Study resources did not support a thorough review of all Department development plans; consequently, the study did not highlight programs that should be terminated to pursue its recommendations. Rather, the specific recommendations should be viewed as important examples within the context of the proposed investment portfolio structure. The study believes that this structure will be valuable to the Department leadership to support the trade-offs required to maintain superiority in a period of flat or declining budgets.

The study drew on the assessment of the 2030 environment to consider the range of strategic contexts or threat scenarios from which capabilities required in 2030 were developed. This top-down perspective was then matched with a bottoms-up assessment of technologies that might address the requirements to select specific technology areas where investments are recommended. In settling on these recommendations, the study emphasized technologies where it judged that current defense programs should be expanded or new areas should be pursued, recognizing that to support operational capability in 2030 the technology must be mature by the early 2020s. The results of this process should not be viewed as a comprehensive list of technology investments for the Department. Rather, it is a set of four areas viewed as high priority for investment to complement currently programmed initiatives.

The study documents four areas: coping with parity, achieving superiority through cost-imposing strategies, achieving superiority through enhancing force effectiveness, and anticipating surprise. They are described in this report, along with suggested investments identified in the study to address each one. The study chose to highlight several areas of interest that were seen as under-attended, meaning they are lacking investment, effort, or focus commensurate with their potential importance to the Department. This was measured by current activities, both inside and outside the Department of Defense. Department leadership will need to trade off available resources, overall strategy, and on-going activities to determine how best to respond to these recommendations.

To assure superiority in 2030, the study deliberately considered only research efforts to those maturing by 2020 in evaluating technologies that will be realistically available in 2030. In actuality, of course, research, development, and deployment are continuous processes. This study, therefore, bears repeating at regular intervals to truly prepare for the world of 2030 and beyond.

Coping with Parity

This approach responds specifically to the challenges expected as a result of the technologically *flatter* world expected in 2030. Many of the capabilities on which the U.S. has relied in recent wars may be vulnerable in the future to adversaries with growing technical sophistication and economic strength. Investments in this category must be focused on either hardening critical operational capabilities in the face of future threats or developing new technologies or techniques to achieve the capability in a totally new way that anticipates and trumps expected adversary countermeasures. The analytic foundation required to identify investments in this part of the portfolio requires horizon scanning to forecast technologies available to the adversary and red teaming to determine

how the technologies might be used to defeat or degrade capabilities on which the U.S. has become dependent.

Achieving Superiority through Cost-imposing Strategies

Historically, the U.S. pursuit of capability superiority has resulted in technically complex, expensive equipment. While the resulting capability has been dominant, this cost and complexity has often limited the number of systems that can be purchased. Also, in certain cases, the adversary has been able to field inexpensive systems, such as improvised explosive devices, that can, at a minimum, challenge the effectiveness of U.S. capabilities and tactics. The low cost of such techniques allows the adversary to build, use, or lose many of them.

Through such approaches as designing low-cost systems that are acquired in large numbers or creating systems that greatly expand operational flexibility, it should be possible to develop capabilities that are less expensive for the U.S. to deploy than for an adversary to counter. In this way, the U.S. can shift the cost advantage to its benefit.

Achieving Superiority through Enhancing Force Effectiveness

The study recommends that the Department broadens its approach to achieving superiority by exploring new ways to enhance effectiveness of the professional military force. Because one of the anticipated enduring advantages for the U.S. is the professionalism and adaptability of the all-volunteer force, investments that enhance the force effectiveness is another productive way to achieve superiority. The study identified three ways to enhance the force: creating more capable equipment that lightens the load carried by individual soldiers, increasing warfighter resilience and performance, and improving training and exercises.

Anticipating Surprise

The study recommends several processes for anticipating surprise. This starts with a robust horizon scanning to monitor global technology development, along with an active red teaming and experimentation activity to explore how adversaries might use emerging technologies to counter U.S. capabilities and tactics. In this context, the use of big data and emerging data analytics was identified as an approach to reduce risks of capability surprise, and to deal with new developments specifically and importantly related to the availability of weapons of mass destruction.

The study also sees significant benefit in hedging against breakthrough developments in emerging technology areas. Examples of such areas include quantum computing,

advanced manufacturing, and synthetic biology. Additionally, the study conducted an extensive review of best practices relative to experimentation, and sees it as a critical tool for reducing the time required to develop and deploy new U.S. capabilities, thereby mitigating capability surprise. In addition, the examination of each technology recommended for investment included an experimentation plan and a strategy to deploy the capability.

RECOMMENDATION 1
USD (AT&L) use four new categories as a taxonomy for broader use in thinking about the Department's technology investment portfolio: coping with parity, achieving superiority through cost-imposing strategies, achieving superiority through enhancing force effectiveness, and anticipating surprise.

Recommended R&D Investments to Cope with Parity

As a result of its review, the study focused on three capabilities on which U.S. military superiority has become critically dependent. For each capability, research and development (R&D) investments are recommended to counter potential adversary threats so as to preserve the U.S. capability. Space defense, precision navigation and timing, and cyber security are three examples of investment to cope with parity.

Satellite Security

Space systems, through their capabilities in surveillance, communications, navigation, and timing, have been critical enablers to U.S. capability advantages of ubiquitous observation, highly coordinated networked operations, and precision weapon delivery. Space also has value to the United States that goes well beyond military affairs. It is an integral part of the civilian communications infrastructure, is the bedrock on which much weather forecasting depends, and serves as an essential tool for disparate industries ranging from agriculture to transportation to entertainment.

As access to space and space technologies becomes cheaper and more widely available, a growing number of countries are acquiring systems and technologies that can deceive, disrupt, deny, degrade, or destroy elements of space systems. As a result, the Department needs to pay more attention to countering the threats to its space-based capabilities in the future, technically flatter world. Because of the cost and complexity of space systems acquisition programs, the study found that most space development

projects paid insufficient attention to self-defense issues. Further, broader initiatives focused on space defense have been sporadic, uncoordinated, and not fully ineffective.

RECOMMENDATION 2

USD (AT&L) and the Director of National Intelligence establish a technology-based space security program that is separate from specific acquisition programs, reports at a high level, and invests $25 to $50 million annually.

It is envisioned that this program be modeled on the existing Submarine Security Program that examines threats within a specific mission context, analytically determines which are possible within the laws of physics and realizable within the state of the art, conducts field tests to verify each threat and characterize it, and proposes countermeasures for those threats that could be realized by an adversary. Established in the 1970s, the Submarine Security Program is led by the Office of the Chief of Naval Operations, is kept separate from day-to-day acquisition, and tasks are performed at affiliated laboratories that have dedicated resources to the program over decades.

Cold Atom Sensing for Positioning, Navigation, and Timing

The critical value of space-based positioning, navigation, and timing (PNT) provided by GPS is well understood. In addition to being essential to many current military operational capabilities, GPS has been integrated into nearly all elements of the economy, providing positioning for aircraft and cell phones and, perhaps even more ubiquitously, providing the timing reference for nearly every communications and computing system.

The study reviewed the status of Defense efforts to decrease the vulnerability of GPS to denial or degradation, particularly by signal jamming or spoofing. A long list of alternatives is being evaluated by the Department for investment, and the study concluded that there was adequate attention focused on this topic. It makes no specific recommendations beyond an encouragement to ensure that adequate resources are provided to implement the selected GPS hardening strategies.

The study assessed the potential of emerging sensing modalities afforded by exploiting ultra-cold atoms to provide precision positioning, navigation, and timing services in the absence of, or with significantly degraded, GPS signals. The study concluded that the feasibility of this cold atom technology to be used for clocks, gyroscopes, accelerometers, magnetometers, and related sensors has been demonstrated, and that the potential precision of cold atom instruments could be several orders of magnitude better than currently available units using other sensing modalities.

RECOMMENDATION 3

DARPA expand and focus its investment in key cold atom components with the objective to create low-power, small volume, affordable components with the maturity to support a production program for advanced inertial measurement units.

Building on this investment, Air Force and Navy (through their R&D organizations) should collaborate on a program to develop and demonstrate an affordable, producible, cold atom inertial measurement unit capable of maintaining unaided 20-meter accuracy for 60 minutes.

Networks Inherently Self-defensible to Cyber Attack

The daunting challenge of protecting civilian and military infrastructure from cyber attack in a world where access to the technology is growing rapidly has been studied extensively by many organizations. This study did not attempt to repeat or expand upon prior efforts; however, it did investigate a novel approach to cyber defense. Rather than global solutions, the study focused on an approach to protect a subset of the network infrastructure that, by its nature, increases the difficulty of a successful attack by an adversary.

A fortunate finding is that this simple approach could significantly protect many supervisory control and data acquisition systems (SCADAs) in municipal water and power systems. The U.S. power grid is one of the most critical systems in the nation and serves both civilian and defense operations. This approach would also be appropriate for some defense mission command systems and air traffic control systems. The study conducted a preliminary red team review of this approach and concluded that it warranted more serious investigation.

RECOMMENDATION 4

USD (AT&L) task DARPA to lead two self-defensible cyber security demonstrations to demonstrate networks inherently self-defensible to cyber attack.

Recommended R&D Investments to Achieve Superiority through Cost-imposing Strategies

As a complement to developing increasingly capable, complex, and costly systems for maintaining capability superiority, the study recommends that the Department think about ways to change the balance of cost in the U.S. favor by developing capabilities that are more expensive for the adversary to counter than for the U.S. to deploy. Three concepts are presented that fall into this category of the recommended investment portfolio. Two of them

emphasize the design and development of low-cost systems that, while possibly less capable as individual units, can be acquired in large numbers. The study validated that quantity can have a quality factor of its own. The third concept has the potential to increase dramatically the operational flexibility of U.S. forces and, in this manner, can pose challenges to an adversary that will significantly raise its cost of defense.

Conventional, Affordable Effects at Intercontinental Ranges

With more capable adversaries, the unfettered access to their homeland that the U.S. has exploited in its recent wars may no longer be achievable. This concern is the motivation for much of the Department's interest in anti-access and area denial capability. Existing bomber and missile systems that can penetrate adversary defenses from long range are expensive, limited in fleet size, and may need to be reserved to achieve vital strategic effects. In pursuit of a capability that could be acquired in large enough numbers to overwhelm adversary defenses or require major investments to defeat, the study reviewed the potential for using current technology to develop an inexpensive, long-range standoff weapon.

The study concluded that current technology can support the development of a long-range conventional weapon at a cost of less than $2 million per unit with the following characteristics:

- Reach a range of 5,500 kilometers (3,000 nautical miles) with a flight time of approximately 10 hours
- Achieve precise attack accuracy of approximately three meters
- Deliver blast fragmentation kinetic effects and some penetration capability
- Maintain uninterruptable situational awareness
- Operate in a degraded GPS or electronic warfare environment

The key to the effectiveness of this system to impose cost is rigorous control of the projected unit cost during development. To foil the natural tendency to add requirements to the system that will increase its complexity and cost, a new management discipline that ruthlessly combats requirements creep will be essential to success.

RECOMMENDATION 5

USD (AT&L) evaluate, design, and develop a low-cost conventional weapon concept that costs no more than $2 million per round, can support other reconnaissance and attack missions, and strike important weapons, sensors, facilities, and infrastructure targets at ranges up to 5,500 kilometers (3,000 nautical miles).

Long-Endurance, Autonomous, Networked Unmanned Underwater Vehicles

The maritime environment presents challenges in anti-access, area denial as potential adversaries increase their investments in littoral defense using improved diesel-electric submarines. The baseline U.S. counterforce capability for these threats is the nuclear attack submarine, a platform costing an order of magnitude more.

To address this challenge, the study evaluated the potential to use state-of-the-art diesel-electric propulsion technology in a long-endurance, low-cost unmanned underwater vehicle. These could be acquired for $10 to $20 million per unit and would cost significantly less than today's manned diesel-electric submarines, estimated to cost $200 million each.

The preliminary operational concept for this system would consist of self-deployed, networked vehicles with sufficient range and endurance to operate persistently within littoral and regional waters. The system would be capable of spoofing and acoustic jamming to degrade, confuse, and overwhelm the adversary's diesel-electric submarines and other underwater anti-access systems, such as sensor grids and shore-based surveillance systems. Networked operations could potentially coordinate multiple vehicles. Manned submarines may be able to perform more complex missions with the added protection provided by the unmanned vehicle fleet.

The key to this concept is designing a system with operationally effective capability at a cost objective of $10 to $20 million per unit. Existing low-cost unmanned underwater platforms developed by Navy oceanographers and laboratories for mapping and survey applications can provide a useful baseline. As with low-cost conventional weapons, the features of this system must be restricted to what can be achieved within cost constraints.

RECOMMENDATION 6

The Chief of Naval Operations task the Naval Warfare Development Command to develop a networked, unmanned underwater vehicle platform to provide acoustic spoofing, jamming, and false target generation.

- A cost target of $10 to $20 million per unit is recommended.
- This program should experiment using existing unmanned underwater vehicle platforms to explore operational concepts.
- The program should generate an early prototype to demonstrate cost feasibility.

Enhanced Vertical Lift

Significantly improving operational flexibility can impose costs by requiring the adversary to engage U.S. forces over a much larger area or against a more varied set of tactics. A major opportunity to implement this is to revamp the Army's current fleet of helicopters.

These vehicles have served the country well with air cavalry weapons systems and utility support missions. However, the limited range, slow speed, and low altitude operating envelope of current helicopters limit operational flexibility by precluding basing the force at remote sanctuaries, rather than forward operating bases. Remote-basing will reduce forward logistics burdens and increase operational ranges, and will increase the cost of defending against U.S. forces.

After reviewing the state of the art for the key component technologies, including advanced rotor designs, optimized airframe aerodynamics, lightweight structures, and increased efficiency engines, the study concluded that these technologies were sufficiently mature to proceed to an X-vehicle demonstration program. Such a program could justifiably target at a five-fold increase in range and a 2.5-fold improvement in speed and operational altitudes.

RECOMMENDATION 7

DARPA utilize its vertical lift X-plane demonstration program as a starting point for achieving advanced, scalable vertical lift that will provide dramatic improvements in operational flexibility with associated game-changing tactics.

Recommended R&D Investments to Achieve Superiority through Enhancing Force Effectiveness

Increasing the professionalism and capabilities of the all-volunteer military provides tremendous advantages. The study identified three approaches to enhance the effectiveness of individual soldiers, sailors, airmen, and marines: lighter-weight equipment technology, warfighter resilience and performance, and training and exercises. The study made specific recommendations toward each of these approaches.

Radionuclide Power to Lighten the Soldiers' Load

At present, the weight of special operations and dismounted soldier packs routinely exceed 100 pounds, with 20 to 30 pounds devoted to power packs and batteries. With the increasing demand for equipment power and the fundamental limits of energy density in electrochemical batteries (3 to 5 kilojoules per cubic centimeters) or fossil fuels (20 to 35 kilojoules per cubic centimeters), there is not much hope for dramatic improvement using current energy technologies.

While there has been a reluctance to consider them, radionuclide sources have energy densities on the order of 100,000 kilojoules per cubic centimeter, and offer the potential for breakthrough performance in power pack endurance. They also represent a dramatic reduction in the weight carried by the dismounted soldier and cost savings from simplified logistic support demands. These sources are used commercially today for medical diagnostic procedures and to power such products as exit signs, albeit in smaller volumes of radioactive material than required for soldier power applications.

The study reviewed the status of development efforts for radioisotope power systems and believes that it should be possible to use this technology safely for military applications. Its potential could be transforming because future soldier equipment—for example, night vision goggles—might be designed with a fully integrated power source that would support the device for its entire lifetime. This could simplify system designs since devices might not need to be protected from power surges as batteries are changed. Eliminating the need to carry and replace batteries should lighten the soldiers' load and free them from the distractions of replacing batteries and eliminate the worries of batteries running out of power.

RECOMMENDATION 8

USD (AT&L) direct DARPA to fund one or two applied research teams to develop and demonstrate safe, affordable, transportable, lightweight radioisotope batteries.

- These systems should provide approximately 5 watts of power continuously for 3 to 5 years.
- In parallel with the technology development USD (AT&L) should convene a working group to address policy, regulatory, and related issues, and to define transition plans and facilitate acceptance of these power sources.

Warfighter Resilience and Performance

Understanding of human biology and the impact of chemical compounds and biological organisms on health and performance is growing at a very rapid rate. Most of this new knowledge is happening outside the Department, in places such as the National Institutes of Health and the broader academic community. Much of this work can be beneficially used to improve the resiliency and effectiveness of soldiers required to perform at high levels in very stressful and demanding environments.

For example, one approach to address the increasing incidence of depression, suicide, post-traumatic stress disorder, and traumatic brain injury suggests supporting optimal brain concentrations of omega-3 fats through adequate dietary intakes. While military populations typically have suboptimal levels of these essential omega-3 fats, extensive intervention trials will be needed to quantify the impact of food or supplements on stress reliance, traumatic brain injury, and mental health impairments.

On a more troubling note, the study learned of extensive use of dietary supplements by soldiers, under little or no supervision, and the effects of this practice are not well understood. On a positive note, there is evidence of the effectiveness of some supplements, such as vitamin-D, ketone esters, creatine, and others, but formal testing in realistic defense contexts have often been limited.

RECOMMENDATION 9

ASD (R&E) oversee a comprehensive program of research, formal trials, and operational experiments to determine the value of selected nutraceuticals, pharmaceuticals, and supplementation regimes aimed at improving warfighter resilience and performance. Further, ASD (R&E) encourage the Defense basic science offices and DARPA to increase its research focus on human-centered technological systems aimed at leveraging and extending warfighter physical and cognitive performance.

- In carrying these out, ASD (R&E) should leverage the knowledge of the Department of Defense Human Performance Optimization Health Science Advisory Committee and the relevant federal agencies outside the Department.
- In addition, USD (AT&L) is strongly encouraged to take actions to strengthen the Department's talent in the life sciences to improve the capability to recognize opportunities and exploit them to create new military capabilities.Next Generation Training

More effective training, using new technologies employed in commercial simulation and education, can significantly advance unit and warfighter performance while simultaneously reducing costs by eliminating some of the need for units to travel to national test ranges for

major training and exercises. While there will always be a role for large-scale training and exercises at major national training centers, the study believes that the technology exists to augment significantly Combat Training Centers to achieve the following characteristics:

- Affordable replication
- Leveraging available local space to preclude, in many cases, the need to travel to centralized sites
- Use of instrumentation capability of operational assets to record events
- Digital libraries with dynamic scenarios
- Ability to exploit real and synthetic techniques
- Optimized training with realistic environmental attributes.

RECOMMENDATION 10

ASD (R&E) work with the Military Departments to implement an experimental campaign using an integrated training environment.

The Military Services should also implement procedures to adopt training techniques proven in commercial settings into their readiness training processes.

Recommended R&D Investments to Anticipate Surprise

The study recommendations that fall in this portion of the investment portfolio focused significant attention on one critical aspect of potential surprise: emerging changes in the threat of weapons of mass destruction. They also suggest an approach for hedging against breakthroughs in specific technologies whose maturity is currently judged to be outside the 2030 timeframe.

Prevention of Nuclear Proliferation

During its review of emerging technologies, the study discovered developments that have the potential to significantly change the threat of weapons of mass destruction across all modalities—nuclear, biological, and chemical. The trend toward a technologically flatter world is generally lowering the barriers to construct weapons of mass destruction, which has traditionally been the purview of technically sophisticated nation states. Many adversaries today use well-understood technology to produce nuclear materials as well as biological and chemical weapons. New production techniques may change the methods used for all weapons of mass destruction, with specific concerns for nuclear technologies.

With global proliferation, the problem of detecting production of weapons of mass destruction and its precursors, known as indications and warnings, has become increasingly difficult. Detection of weapons of mass destruction is becoming a concern for emerging processing capability, and related data analytics to extract information by finding patterns in large volumes of disparate data sets should be applicable. Today, much of the research efforts in big data analytics are driven by commercial applications, and the Department needs to use these methods much more effectively.

RECOMMENDATION 11

The Department and the National Nuclear Security Agency assess the application of modern technology to the challenges of nuclear proliferation.

- Based on the findings of this assessment, USD (AT&L) with USD (Policy), National Nuclear Security Agency (NNSA), Department of State, and the intelligence community should develop goals and requirements for a strategic system to detect indications and warnings for the transformed production of weapons of mass destruction.
- Using the goals and requirements developed by this group, the Defense Threat Reduction Agency should lead a co-located team to carry out a compartmented prospective threat assessment. In addition to subject matter experts from all concerned government agencies, corporate experts in big data analytics with access to intelligence databases should also be involved.

Horizon Scanning

The study identified a number of technologies that are too immature at present for transition to military capability within the 2030 timeframe. This was done with heavy reliance on the existing and effective horizon scanning and net assessment efforts in the Department. The ASD (R&E) horizon scanning function properly includes extensive reach outside the Department to include academia, industry, and coordination with similar activities within the defense establishments of allies.

Horizon scanning is most useful to identify technologies that are immature today, yet have the potential to change the predicted environment. In cases where the question is not *if* but *when*, a hedging strategy is recommended. In finance, a hedge is an investment intended to reduce potential losses. In technology, a hedge is an investment intended to reduce the potential for capability surprise.

Three areas were identified by the study that warrant hedging: additive manufacturing, synthetic biology, and quantum computing. These technologies share some common characteristics, including significant global research investment and strong driving forces

other than military applications that motivate this research. While major investments are not recommended, it would also be a mistake to ignore them and be surprised and unprepared when the technical breakthrough happens.

RECOMMENDATION 12

USD (AT&L) support activities that maintain continuous scanning of the technology horizon and assessment of emerging defense problems.

- Programs are needed to interact with industry and other government organizations to monitor the status and specific milestones of identified emerging technologies, with the goal to determine whether the technology is mature enough to require concerted defense funding.
- In parallel with the monitoring activities, the Department should also conduct conceptual application studies to explore how the technology might be exploited to create capability advantage when it matures.
- Mechanisms should be established and maintained to ensure that senior Department leadership is alerted when potential high impact technologies are identified.

Use of Experimentation to Avoid and Create Surprise

Effective experimentation can be an innovation enabler that provides the opportunity to plan for the introduction of new technology and prepare future defense capability. The study team observed that such a robust approach to experimentation was core to the Department's strategy in the early 1990s that sought to take advantage of the explosion in commercial information technology. At the heart of this approach was the desire to explore, discover, analyze, and understand the potential of emerging technologies and their ability to enhance military capability and doctrine. Over time, the defense environment has become increasingly risk averse, and experimentation has moved toward scripted demonstrations, testing, and training. As the Department confronts the challenges associated with the end of the wars and reduced budgets, the study recommends a reinvigorated approach to experimentation that incorporates today's best practices in experimentation.

RECOMMENDATION 13

USD (AT&L) foster a robust experimentation program that includes discovery and analysis of the potential of new technologies rather than only testing and evaluating at development milestones.

Military Department service acquisition executives should develop processes to better share use of tools and infrastructure that exist in training- and simulation-based experimentation domains.

1 Introduction

In March 2012, the Under Secretary of Defense for Acquisition, Technology, and Logistics (USD (AT&L)) directed the Defense Science Board to "conduct a study of emerging technologies that will enable the next generation of dominant military capabilities to be in development or fielded by 2030."

The desired products of the study were described as (1) a set of recommendations intended to guide the Department's research and development investments in applied technology and technology demonstrations over the period of 2014 to 2020; (2) mapping of the identified technologies to applications and capabilities that may be enabled; and (3) for a select set of promising technologies, experiments or concept demonstrations that would foster innovation and provide entry ramps to enhance operational capabilities via block upgrades to existing systems or as entry ramps to new systems and operational concepts.

To address this charge, the Board assembled a study membership of national leaders in science and technology. The study met over the course of several months to explore required capabilities, global technologies, and principles of experimental design with a focus to identify key investments for superiority in 2030.

The World in 2030

To identify technologies and innovations that will enable superior military capability in 2030, the study endeavored to envision the world of 2030. This began with a survey of global trends from today through 2030. Some of the most striking trends forecast significant changes in demographics, resource availability, economic leadership, and technology development. While forecasting is always a precarious activity, it becomes ever more important during an era of increasing uncertainty.[1]

Demographic Changes

The most fundamental demographic fact is that individuals born in 2010 will be 20 years old in 2030. Other projections and implications are more complex and subject to

1. P.E. Tetlock, *Expert Political Judgment: How good is it? How can we know?* (Princeton University Press, 2005).

change as time passes.[2] The current world population is approximately 7 billion people, and by 2030 is projected to grow to almost 8.3 billion.[3] This growth will not be globally uniform, but populations will undergo a range of shifts in age, wealth, and location.[4] This overall trend, shown in Figure 1, highlights the rapid growth in Africa and the Middle East, as compared to slow or negative population growth in Europe.

These shifts also predict a growing global middle class, which will increase the demand for resources such as food, water, and energy.[5] Many countries are also expected to see a population contraction within the traditional workforce age and an unprecedented

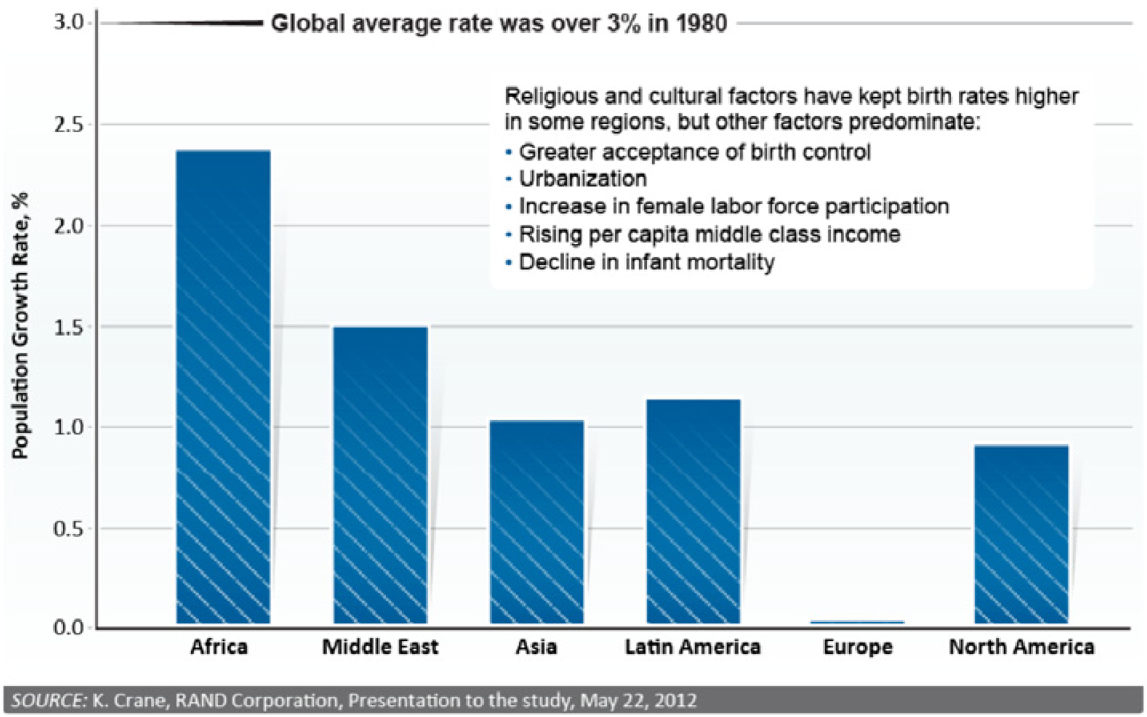

Figure 1 Global Population Changes in 2012.

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2. R.J. Danzig, *Driving in the Dark: Ten propositions about prediction and national security* (Center for a New American Security, 2011). Available at time of press at http://www.cnas.org/drivinginthedark
3. World Bank Data Catalog, *Total Population (2012)*. Available at time of press at http://data.worldbank.org/indicator/SP.POP.TOTL/countries?display=graph
4. U.S. National Intelligence Council, *Global Trends 2030: Alternative Worlds* (2012). Available at time of press at http://www.dni.gov/files/documents/GlobalTrends_2030.pdf
5. D. Rodhe, *The Swelling Middle*, (Davos 2012, Reuters). Available at time of press at http://www.reuters.com/middle-class-infographic

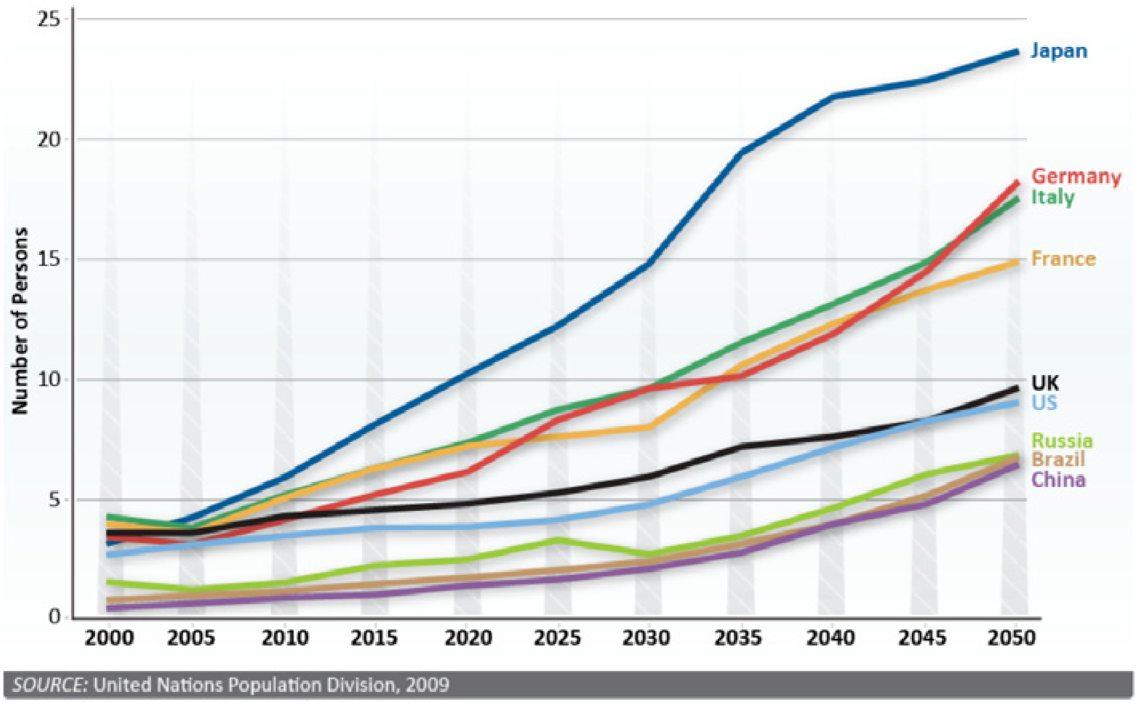

Figure 2 Number of People Aged 85 Years and Older for Every 100 Working-age Adults.

proportion of seniors, as shown in Figure 2.[6,7] The increasing proportion of seniors is a new phenomenon in human history and inverts the population pyramid that has described population until recently.

In addition to the challenges an aging population will place on health care, changes in working-age populations could affect economic well-being.[8] More developed regions facing a decline in economic growth may be forced to adopt potentially divisive solutions such as increased immigration. Increasing global opportunities for a mobile, skilled workforce will challenge many political, social, and cultural systems. In states where language and cultural barriers make the integration of large immigrant communities difficult, internal conflict may result from erosion of social cohesion. It may also spark external conflicts when, for example, immigrant populations request protection from the

6. GE Data Visualization, *Our Aging World*. Available at time of press at http://visualization.geblogs.com/visualization/aging/

7. RAND Corporation, *The Fall and Rise of Working Age Populations, How Demographics Will Change the World Through 2050* (2012). Available at time of press at http://www.rand.org/publications/randreview/issues/2011/winter/world.html

8. M.C. Libicki, H.J. Shatz, and J.E. Taylor, *Global Demographic Change and Its Implications for Military Power* (RAND Corporation Document MG-1091-AF, 2011). Available at time of press at http://www.rand.org/pubs/monographs/MG1091.html

country of their birth. Immigration laws designed to protect or encourage brain drain will become friction points as will governance of these issues in general.

Immigration is often accompanied by urbanization.[9] Urbanization will exacerbate resource distribution, especially as increased populations translate into resource scarcity.

Resource Availability and Climate Change

The pressure on resources spans the availability of clean water, affordable food, and viable energy sources.[10] Water is likely to be one of the most influential stressors. National intelligence estimates predict annual global water requirements will reach levels 40 percent above current sustainable water supplies and the Organisation for Economic Co-operation and Development (OECD) suggests that nearly half of the world's population will live in areas of serious water stress by 2030.[11]

Competition for water is likely to impact food production, and shifting food production centers will impact prices. Population increases and increased urbanization may require more energy to distribute food to the locations where needed, thereby increasing cost. Increasing economic well-being drives dietary changes and will change agricultural production priorities, especially as demand for meat products increases.

Finally, energy demand is expected to rise dramatically, by as much as 45 percent, as more populations move up the development scale. The location and distribution of energy resources will continue to be dynamic. The dramatic increase in natural gas production in the United States through hydraulic fracturing was completely unforeseen as recently as 2009, making all future energy forecasts suspect. Being resource-rich will certainly contribute to economic vigor in the United States, but capitalizing on this new resource will depend on the ability to distribute the goods produced as a result of relative energy price advantages. Selling agricultural, energy, and manufactured products require ready access to the global commons, and all global distribution mechanisms are ready targets for adversaries of the United States seeking to gain competitive advantage.

Economic Leadership

Economic trends are moving the world toward a multipolar economic environment, with the economies of China and India driving a competition for leadership globally, and

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9. United Nations, World Urbanization Prospects (2009).

10. Transatlantic Academy, *The Global Resource Nexus –The Struggles for Land, Energy, Food, Water, and Minerals* (2012). Available at time of press at http://www.transatlanticacademy.org/publications/global-resource-nexus-%E2%80%93-struggles-land-energy-food-water-and-minerals

11. Food and Agriculture Organization of the United Nations, The State of the World's Land and Water Resources for Food and Agriculture: Managing Systems at Risk (2011).

requiring the West to embrace strong regional partnerships for economic success and stability.[12] Offshoring of manufacturing capabilities resulted from capital inducements such as wage structures and tax rates, weaker environmental regulations or enforcement, or available resources. These shifts are causing lowered standards of living as a result of the loss of fabrication facilities, and are further exacerbated by subsequent losses in underlying technology, such as the migration of supporting design and testing capabilities. Recent financial, political, and economic crises have created significant uncertainty regarding the continued sustainability of the current innovation system that feeds the defense technology base.

Global Technology Development

The increasing pace of technology discovery and development is fueled by the broadening worldwide access to information, education, materials, tools, and manufacturing capabilities.[13] Technology trends now empower nontraditional players to exploit and even take the lead in producing niche technology solutions. As individuals and small groups are empowered through easy access to crowd-sourced, remote expertise; decreasing costs using local, low-signature manufacturing; and increasing access to the global marketplace, they will seek to create novel solutions to local or global problems. This could relieve some of the growing resource pressure through more effective and affordable approaches to energy conservation and production, water purification and desalination, and agricultural production.

A further consequence of global technology development is the likelihood that this knowledge will be used to produce weapons and military capability, thus fueling new and unexpected threats from states, organizations, and individuals not traditionally considered to be sources of technical challenge. Throughout history, technology has contributed to military capability: guns defeat arrows, missiles defeat cannonballs, and satellite communications defeat word of mouth. However, the cost of unbounded exquisite technological sophistication is high. Military actions requiring expensive platforms, and equipment with long logistical support tails generate vulnerabilities ripe for exploitation, as the use of improvised explosive devices in Iraq and Afghanistan demonstrated, where a technologically unsophisticated adversary created damage that was disproportionate to the technological and financial investment. By 2030 the increasing distribution and linkages available for technology development will likely enable creation of similar destructive asymmetries on a global scale.

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12. A. Subramanian, *Eclipse: Living in the Shadow of China's Economic Dominance* (Peterson Institute for International Economics, 2011).
13. Envisioning Technology, *Envisioning Emerging Technology for 2012 and Beyond (2012)*. Available at time of press at http://envisioningtech.com/envisioning2012

Specific areas of emerging technology that are considered to have significant disruptive potential in the 2030 timeframe, either individually or by enabling established areas of research in new ways, include: large-scale storage, manipulation, and analytics for data, as well as significant changes in cyber capabilities and vulnerabilities; quantum information sciences; the biological sciences; and research in power and energy. For example, as data become more available and the associated capabilities to access, manage, and analyze them progress, the ability to monitor the behavior of individuals and groups will grow with the potential for predictive models and more effective engagement during periods of stability.

Today's challenge is to invest in technologies that will provide significant, game-changing advantages against both peer and nonpeer adversaries, within the constraints of declining defense budgets. In assessing these investments, current and projected military deficiencies, envisioned future conflicts and global stressors, emerging research and development in a broad range of disciplines, and anticipated growth of relevant nonmilitary commercial technologies, in the U.S. and elsewhere, must all be considered.

Assessment of the Strategic Environment and Context in 2030

The only certain aspect of the threat environment in 2030 is that threats will be uncertain and dynamic and that they will challenge many traditional strategies of containment and dominance. Interaction of these trends will once again extend complex conflicts into the global commons—areas once held in common rather than owned (*e.g.,* air, sea, and land) and into the new commons, such as outer space, undersea, and notably, cyber space.

Implications for the U.S. Global Position

Global trends over the next two decades will prove a mixed bag for the United States. Demographic challenges exist in the U.S., but appear to be less severe than those projected globally for both the aging population and the youth bulge. The nation has a rich cultural history of immigrant populations, and many realize that immigration is a major contributor limiting the impact of an aging population and promoting innovation. Natural resource availability will continue to be dynamic. The U.S. energy posture supports independence due to a boom in natural gas production. Finally, clean water and agricultural production are relative positions of strength, but can disappear with an unexpected natural disaster or through mismanagement.

Technology trends are equally mixed. By many metrics—patents filed, fraction of research and development investments, Nobel prizes awarded, and so on—U.S. investments in science and technology have paid off handsomely. This success has propelled many of the world's developing states to emulate the U.S. model, and China, India, and others are devoting an increasing amount of their capital resources to science and technology.[14,15] This may have long-term implications for the U.S. position. Current trends in science, technology, engineering, and mathematics education, and R&D funding, may have implications for the U.S. and global economic structure.

With increased global access to information, knowledge, capital, materials, and manufacturing processes, technology developed in the U.S. can no longer be assumed as the *de facto* standard for the rest of the world, nor should the U.S. assume that it will have access to cutting edge technology developed in other countries. The impact of this trend on military superiority is clear—U.S. adversaries can no longer be assumed to be less technologically sophisticated. By 2030, all countries will have access to and the ability to employ the underlying technology in a wide range of capabilities: computing and processing, communications systems, satellite imagery, navigation aids, sensing systems, biotechnology, pharmaceuticals, and other technological tools.

Strategic Contexts in 2030

The study used the assessment of the global environment in 2030 to consider the range of strategic contexts or threat scenarios that the U.S. may face in the coming decades. These potential scenarios were then mapped against defining characteristics in order to identify the capabilities that will be needed in 2030. The process entailed determining desired game-changing capabilities and fact-finding from experts in a number of fields and then mapping these desired capabilities to enabling technologies. This resulted in a list of specific capabilities and technologies needed to ensure superiority in 2030.

The strategic contexts in 2030 and desired strategic capabilities are summarized in Table 1 and are described in detail in Appendix A. In these examples, a broad range of potential threats can accompany each of these complex potential 2030 scenarios. In order for the Department to respond rapidly and cost effectively to these emerging threats, new capabilities must be exploited. These new capabilities may be achieved by leveraging new technology development, creating open architectures, or implementing block upgrades of existing capabilities.

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14. Battelle, *2012 Global R&D Funding Forecast* (2011). Available at time of press at http://battelle.org/docs/default-document-library/2012_global_forecast.pdf?sfvrsn=2

15. National Bureau of Statistics of China, *2011 National Science and Technology Funding* (2012). Available at time of press at http://www.stats.gov.cn/tjgb/rdpcgb/qgrdpcgb/t20121025_402845404.htm

Table 1 Strategic Contexts and Desired Capabilities

2030 Strategic Contexts	Desired Strategic Capabilities
• Homeland protection • Peer or near-peer military competitors at the nation-state level • Regional adversaries • Security partners and alliances • Failed or failing states • Stateless threats • Transnational organized crime • Transnational corporations • Favorable access to the commons • Individual actors • Humanitarian assistance and disaster relief	• The capability to defend space assets or to be able to operate without existing space capabilities • Inherently self-defensible systems from cyber attack • The capability to field smaller, lethal, survivable forces for sea, air, and land • World-wide, multidomain situational awareness • Rapid adaptation and generation of cheaper capabilities • Robust tracking and defense of weapons of mass destruction • Capable, autonomous systems • Enhanced human adaptability performance • Advanced manufacturing

Emerging Technologies

The study evaluated a wide range of emerging technologies. The primary objective was to assess technical developments that could be brought to fruition in the next two decades, determine which could have a major impact on useful military capabilities, and to highlight them to the Department, along with recommendations of specific actions that the Department might take to bring them to fruition. The observations that follow did not arise from strict adherence to a rigorous process. Instead, they grew from thoughtful discussions among the group who collectively have depth and breadth of experience in defense science and technology and share an abiding interest in national security. The initiatives presented are not intended to be comprehensive and should be assessed within the limitations of the process.

Throughout these deliberations, significant attention was paid to three criteria to differentiate the numerous technologies initially considered:

1. Relevance to Department of Defense missions
2. High degree of impact on those missions
3. Currently under-attended by Department of Defense focus or budget

Criteria (1) and (2) represent tacit recognition that, while all advanced technologies have certain appeal, the Department needs to focus on those that make the most difference to important Department of Defense missions. Criteria (1) and (2) are intended to help achieve that focus. Criterion (3) is intended to help resist the temptation to recommend that the Department take further action in an area where they are already supporting important work, and in which that level of support is the product of thoughtful

and balanced consideration. Criterion (3) also represents recognition that substantial technical progress today is made globally without dominant control or funding from the Department of Defense. The clear implication is that the Department must do a better job of harvesting the fruits of global technology investment to complement and increase the efficacy of its own investment.

Thus, in summary, while mitigating technical surprise for the Department of Defense across the spectrum of both adversary and commercial technology investment was primary, these discussions balanced the directive to cast a broad net with the imperative to focus resources where they will matter most.

Table 2 summarizes these findings for several technology areas with explicit reference to the three criteria discussed above. Judgment led the study to further investigate some technologies, to conclude that current programs adequately covered others, and for some cases, the current state of the technology is too uncertain to make a strong investment recommendation at this time. A summary of technologies that will likely reach fruition beyond 2030 is included in Appendix B. This uncertainty in the potential success of these technologies is further exacerbated by the expectation that significant work will be done in these areas outside of Department control. In these cases, a hedging strategy is

Table 2 Illustrative Examples of New Technologies Considered in the Study

Technology	Enhanced Capability	Relevant to DoD?	Trans-formative?	Under-attended?	Study Approach
Warfighter resilience and performance	Human resilience and performance	yes	yes	yes	Investigate
Ultra-precise navigation and timing	Space capabilities	yes	yes	yes	Investigate
Compact high-energy density power, long-lived low power	Smaller, lethal, survivable forces for sea, air, and land	yes	yes	yes	Investigate
Big data analytics	Robust tracking and defense of weapons of mass destruction	yes	yes	yes	Investigate
Sensors	World-wide, multidomain situational awareness	yes	yes	no	Covered
Synthetic biology	Rapid adaptation and generation of cheaper capabilities	yes	yes	no	Hedge
Advanced manufacturing	Rapid adaptation, reduced logistics tails	yes	yes	no	Hedge
Quantum computing	Inherently self-defensible systems from cyber attack	yes	yes	no	Hedge

recommended that protects the interests of the Department without making an unjustified commitment of resources.

Investment Framework

Four themes emerged as a result of these efforts, which are needed for the United States to:

1. Cope with global parity
2. Achieve superiority through cost imposing strategies
3. Achieve superiority through improving the effectiveness of the force
4. Avoid surprise

These four themes form the basis for an investment strategy to achieve military superiority in 2030 that recognizes the future environment of global technology availability and limited defense budgets. They are a complement to the primary current investment focus of seeking increasing technical capability and complexity, often at a very high cost.

Coping with parity

Longstanding U.S. military advantages are at risk in a world of technological parity. There is ample evidence that adversaries do, or will soon, possess technical capabilities on par with the U.S. in certain important niches. Technological parity does not necessarily mean the U.S. cannot compete militarily but that participation in conflicts may impose significantly higher costs. The study concluded that rather than cede parity to adversaries, the U.S. should shape investments to maintain its competitive advantage in key capabilities on which it has come to rely. Three critical capabilities were identified as exemplars of this investment strategy: satellite security; cold atom sensing for positioning, navigation, and timing; and networks inherently self-defensible to cyber attack.

Space exploitation has created competitive advantages for the U.S. national security establishment in such areas as denied area sensing, communications, and navigation. It has also led to a large commercial market. A significant contributor to this situation arose from treating space as a portion of the global commons coupled with clearly delineated strategic missions that supported definitive behavioral guidelines. For example, the attack by the former Soviet Union on U.S. early warning satellites would have been clearly regarded as a strategic attack. The increasing use of U.S. national assets in support of tactical missions and the increasing number of states with space capabilities blurs the line

between strategic and tactical, local and global, and increasingly throws into question the unfettered access to space capabilities in 2030.

The dependence of the U.S. on network commercialization to exploit cyberspace is well chronicled, and its loss would be a significant reduction in U.S. capability. Cyber capabilities enable invaluable situational awareness, fast decision-making, and effective force application.

Space-based GPS provides precision positioning, navigation, and timing, and provides a number of advantages to the U.S. military, such as all-weather precision weapons. Maintaining access to precision time and position is absolutely essential to many aspects of military operations.

Achieving Superiority by Imposing Cost

There are many paths to adjusting relative advantages between the U.S. and its adversaries to achieve superiority. One mechanism is to develop cost-imposing strategies, which will divert adversary resources away from its own improvements. For this to work, U.S. forces must be able to deliver sufficient quantity and capability to force an adversary to react with capabilities that have equal or higher cost. Simply put, quantity has a quality of its own, especially when quantity can be coupled to enhanced operational flexibility. Focused investments are needed to take advantage of technological advances in design, manufacturing, control, and operations that can produce higher quantities at lower cost—and that will force more costly responses from adversaries.

Achieving Superiority by Enhancing Force Effectiveness

A second mechanism to achieve superiority is to increase the effectiveness of U.S. forces. The caliber of the U.S. all-volunteer force is a significant advantage that should be able to be maintained with appropriate technology investment. Today's unmounted soldier is weighed down with up to 30 pounds of batteries, significantly impacting endurance and resilience. The potential to significantly reduce this load with no loss in available power reserves would grant a tremendous advantage. The resilience and performance of individuals on the battlefield today also depends on the nutrition and supplements that are available to them. Research in this area indicates that there is low-hanging fruit to improve both cognitive and physical performance. Warfighter-centered systems technology that can improve human-machine teaming is another area with many identified benefits.

A major contributor to today's effective U.S. military forces is their professionalism and competence realized as a result of rigorous and realistic training. However, current training

is achieved on dedicated ranges that are limited in throughput, are limited in their ability to quickly adapt to new scenarios, and are costly. Adopting and shaping commercial gaming technologies to U.S. military needs have been identified as a path to reduce costs, increase throughput, and enhance adaptability to emerging threats. If properly configured, the future training environment will play a substantial role in maintaining and distributing knowledge and know-how in the dynamic global environment envisioned in 2030.

Avoiding Surprise

No matter how well planned and executed, technology investments will still likely result in gaps in exploitation and vulnerabilities in capabilities. For example, the same technologies that provide the empowered individual an unprecedented ability to communicate and coordinate activities spanning the globe may also create capability to coordinate and conduct terrorist attacks. Technology advances may also enable more paths to manufacture and exploit weapons of mass destruction.

Horizon scanning and hedging strategies are needed to maintain awareness and capabilities to be able to rapidly move on new technology advances. Equally important are innovative experiments and exercises that can identify gaps and can verify solutions quickly and effectively.

It may be fortunate that the amount of information generated and consumed globally today is unprecedented.[16] In the future, merely creating and making data available will not provide anyone the upper hand; only those who are able to analyze and draw conclusions from the massive amounts of data collected will be able to remain competitive.[17] The Department must compete in this environment to avoid surprise and protect U.S. assets.

With a future of constrained budgets, the current approach to understanding emerging capabilities through broadly funding all areas of potentially relevant technologies will be challenged.[18] Adversaries of the U.S. will likely gain advantages in niche weapons development and new strategic capabilities, as well as some areas critical to existing supply chains. The U.S. will need to adapt rapidly to surprises in both the pace of development and new uses of technologies worldwide.

Finally, enhanced experimentation is capable of improving understanding and preparation when capability surprise occurs. The importance of effective experimentation cannot be

16. E. Schmidt, CEO of Google, stated "Every two days now we create as much information as we did from the dawn of civilization up until 2003," at the Techonomy Conference, August 4, 2010.

17. J. Jonas, Presentation to the Defense Science Board, May 24, 2012.

18. Department of Defense, *Sustaining U.S. Global Leadership: Priorities for 21st Century Defense* (2012). Available at time of press at http://www.defense.gov/news/defense_strategic_guidance.pdf

overemphasized. A hard lesson learned over the last decade of war was that many technologies touted as ready for battle required substantial development before they were useful to the warfighter.

RECOMMENDATION 1

USD (AT&L) use four new categories as a taxonomy for broader use in thinking about the Department's technology investment portfolio. These categories are coping with parity, achieving superiority through cost imposing strategies, achieving superiority through enhancing force effectiveness, and anticipating surprise.

Recommendations in this Report

The remainder of this report presents the details behind the technology investment recommendations that are the primary output of the study effort.

Chapters 2 through 5 present the specific recommended investment areas, sorted within the context of the strategic capability goals that are the basis of this report. Each concept is described in detail along with the required resources and a preliminary program structure that includes the experiments and demonstrations that will facilitate integrating the capability into deployed systems and programmed development projects.

These sections are supplemented by several appendices that provide further background on the desired strategic capabilities in 2030, technologies beyond 2030, and best practices relative to experimentation.

2 Key Investment Opportunities to Cope with Global Parity

The convergence of cyber and space capabilities is rapidly guaranteeing that losing competitive advantage in one will significantly affect the other. Coping with growing global parity in these areas will be of primary importance in the world of 2030.

Satellite Security

Space Capabilities Advantages and Dependence

Space is the fourth domain in which nations have competed for advantage: first land, then sea, then air, and now space. To date, the use of space for military purposes has been limited in scope to a few nations using a rather narrow set of capabilities. The first countries to achieve military capabilities in space were the U.S.S.R. and the United States. They were followed by China, Japan, and the nations of the European Union. Today, Israel and India have developed indigenous capabilities to operate in space and, presumably, will be joined by others over the next decades.

Space has tremendous value to the United States that goes well beyond military affairs. While many current space systems are critical to U.S. military superiority, space is also an integral part of the commercial communications infrastructure, is the bedrock upon which much weather forecasting depends, and serves as a critical—and sometimes, enabling—tool for disparate industries ranging from agriculture to transportation to entertainment. It is, in short, a core element of the U.S. economic prowess.

Today, adversaries of the U.S. may not be as reliant on space—but they recognize U.S. dependencies. The remarkable strategic and tactical military and intelligence capabilities that the U.S. has developed, in no small way, leveraged by its capabilities in space, make it clear that any nation that wishes to engage the U.S. militarily in the future has to take into account these capabilities and counteract them if possible. To cope with parity in 2030, Department space defense efforts require stronger integration, more consistent funding, and a deeper technical foundation.

To date, space capabilities used by nations for military affairs have been primarily limited to surveillance, communications, navigation, and timing. Most of these space assets were developed during the Cold War when it was assumed that space was secure from attack. Indeed, treaties limit or prohibit many military activities. Rules notwithstanding,

terrestrial weapons that threaten these assets exist today. However, no nation has yet indicated their use with hostile intent.

Regardless of current operational behavior or current treaties, it can only be assumed by military planners that military engagement in space could expand to include the same families of offensive and defensive capabilities found in the other war fighting domains of land, sea, and air. That is, space assets would be attacked overtly and covertly and they would be attacked not only by land, sea, and air platforms but also from space platforms. To respond to such attacks, the Department would have to address defense, reconstitution, and operations without space. Satellites would have to recognize when they are under attack and be able to respond appropriately, often autonomously. A key defense against attack may not be in the satellites themselves but in the architecture of the constellation. For example, thousands of small objects in space would be harder to destroy than a few large ones.

Finally, space assets are of little use without their ground station support infrastructure. Certain situations may arise when the most vulnerable part of a space-based system is the ground segment that supports it. Survivability of both ground support stations and launch facilities would be required for effective space restoration.

As access to space and space technologies becomes more widely available, many countries are acquiring systems and technologies that can deceive, disrupt, deny, degrade, or destroy elements of space systems. Of particular concern is the Global Positioning System (GPS) that provides precise positioning, navigation, and timing for both military and civilian devices.

The effects of potential adversarial counter-space capabilities can be reversible, such as satellite communications jamming and cyber attacks, or nonreversible, such as from direct ascent anti-satellite weapons and high-energy lasers. Satellite systems are also vulnerable to natural and environmental threats such as weather, space debris, competition for limited resources such as orbital positions and electromagnetic spectrum, and unintentional signal interference. While not intended to do harm, these natural and environmental threats are causing increasing concern due to potential impact on space operations.

Space Protection Program

The United States has recognized both the importance of space systems and the challenges to them that have to be addressed. A variety of issues dealing with the protection of space assets ranging from governance to policy to technology investment have to be addressed. This proposal is focused at the latter component of an overall space security and defense program: the investments that are required to address the real challenges likely to arise given the constraints of physics and the state of the art in relevant technologies.

The specific recommendation is the USD (AT&L) and the Director of National Intelligence establish within any overarching program, a technology-based space security program focused on advanced threats, countermeasures, and a long-term resilient space system architecture.

It is envisioned that this program be modeled on the existing Submarine Security Program. This program, which has been in existence since the 1970s, examines potential threats to ballistic missile submarines within a specific mission context, analytically determines which are possible threats from a perspective of the laws of physics, and which are realizable threats from a perspective of the state of the art; conducts field tests to verify the threat and characterize it; and, finally, proposes countermeasures for those threats that could be realized by an adversary. All of these activities are informed by intelligence throughout. However, this process is not dependent on intelligence information that an adversary actually has such threat capabilities fielded or in development: it focuses on what might be possible.

The submarine security program was first established by the then-Director of Defense Research and Engineering, Dr. John Foster. It is led within the Office of the Chief of Naval Operations and kept separate from day-to-day acquisition. It is performed at affiliated laboratories that have dedicated resources to the program over decades. Thus, there is an accumulated body of knowledge and a cadre of subject matter experts that can be (and have been) called upon to address threats to ballistic missile submarines that have been newly identified or hypothesized. Threats that were (and still are) impossible to realize within the laws of physics are dismissed. Threats that were not possible within the former state of the art but are now possible under the current state of the art are investigated further. Countermeasures are proposed after verifying their effectiveness with sea trials. Note that countermeasures may be technical in nature (*e.g*., a hardware or software solution) or operational in nature. Throughout the process, close ties are maintained between the technical community and the operational Navy to ensure that operational realism is maintained.

The level of effort over the years has varied, but generally has been on the order of tens of millions of dollars supporting over one hundred engineers, scientists, and technicians dedicated to this task.

A similar Air Force program was established in 1979 for the then-emerging radar low-observable or stealth air vehicle technology. The program established early measurement campaigns to evaluate the viability and effectiveness of stealth technology. The program also established a core team of technical analysts for assessing the resistance of stealth technology with a range of potential measures and countermeasures. The result was a measurements-based approach for evaluating the survivability of air vehicles in challenging scenarios. The program continues at a significant scale through the U.S. Air Force.

Program Characteristics

The vision for a Space Protection Program begins with identification of an office within the Department of Defense to oversee the program. This office should not be responsible for acquisition of space systems. The operational units and intelligence components that will support the program should also be identified, as well as the laboratories that will carry out the work.

Once the program is established, the combatant commands should identify all mission contexts that require protection and establish the programmatic conditions.

The technical program will be charged to systematically identify potential threats and to understand and communicate the state of the art and the state of the practice globally. They will develop potential countermeasures, either operational or technical in nature, and verify these countermeasures with field trials in close cooperation with operational commands.

Throughout this program, all parties would operate under the assumption that the program would exist over the long term, that assembled information would be readily available for future use, and that a cadre of subject matter experts would be maintained.

RECOMMENDATION 2

USD (AT&L) and the Director of National Intelligence establish a technology-based space security program that is separated from specific acquisition programs, reports at a high level, and invests $25 to $50 million annually.

Charter program to:

- Use the Submarine Security and Air Force Red Team programs as models
- Remain independent of procurement activities, conflicts, and adversary activities
- Focus on advanced threats, countermeasures, counter-countermeasures, and a long-term resilient space system architecture
- Assess threat feasibility based on physics and the state of the art
- Evaluate impact on mission performance
- Develop candidate countermeasures
- Maintain continuity and build competencies over time
- Define and evaluate experiments to verify threats and test potential countermeasures

Cold Atom Sensing for Positioning, Navigation, and Timing

Positioning, navigation, and timing (PNT) has evolved over the decades to be largely implemented using space-based assets. Space-based positioning, navigation, and timing has grown into a global utility with multiuse services that are integral to national security, economic growth, transportation safety, and homeland security, and are an essential element of the worldwide economic infrastructure. GPS is the U.S. implementation of space-based positioning, navigation, and timing, and is a key component of multiple sectors of U.S. critical infrastructure. Yet as national security and the economy have become ever more dependent upon reliable positioning information, it has become in some ways even more vulnerable to interference, jamming, and spoofing. The likelihood that U.S. advantages provided by precise, satellite-based navigation are threatened increase dramatically in a future world of technical parity.

Protection of precise positioning, navigation, and timing is critical in highly contested environments, where it may be affected by both intentional and unintentional radio frequency interference. The Department has available several well-understood actions to reduce vulnerability of military platforms to the anticipated threats to global navigation satellite services:

- Changes in power and waveform transmitted by GPS can significantly mitigate a broad set of current and emerging threats.
- Relatively simple modifications to GPS antennas and receivers can be made to improve their signal reception, improve adaptability, and lower susceptibility to interference and jamming.
- Increased resilience in the GPS constellation could be afforded through additional transponders on other constellations, such as Iridium satellites.
- Other nations have developed or are developing global navigation satellite systems, such as the Russian GLONASS, European Galileo, and others. Within a few years, there will be over 900 signals, with only 100 provided by the United States. Many of these radio navigation signals could be integrated into U.S. military systems; indeed, they are already being used in commercial multisystem user equipment such as the Topcon G3.
- Terrestrial infrastructure-based timing and distribution is possible through deployable alternative air-, sea-, or land-based beacons and organic platform navigation and timing.

Each of these areas should be leveraged to their fullest extent. In several situations, however, these methods do not provide adequate margin and alternative technologies are needed. These situations include proposed long-endurance unmanned underwater and

aerial vehicles, small unit operations in urban environments, and long time-of-flight missions.

For precise timing, the progression of high accuracy, quantum-based atomic clocks will likely satisfy the needs of critical national infrastructure in 2030. Two DARPA programs are making good progress. The Chip Scale Atomic Clock (CSAC) program reduced drift to less than 50 microseconds per month with a 15-cubic centimeter, 30-milliwatt device.[19,20] The Integrated Micro Primary Atomic Clock program (IMPACT) is projected to further reduce timing drift by three orders of magnitude, all in a 5 cubic centimeter, 50 milliwatt package.[21] If this development effort is successful, accurate time will be possible in systems with low size, weight, and power for several days with little degradation. To ensure adequate timing performance by 2030, it is critical to U.S. defense missions that this development and commercialization pace is maintained.

Achieving Navigational Accuracy and Precision

Depending on the mission duration and the navigational accuracy required, different classes of navigation accuracies may be required. The range of tactical, navigation, and strategic grade systems balance cost against performance and reliability, as indicated in Figure 3.

A commercial accelerometer, such as is available on a mobile smartphone, is also shown. While very inexpensive, these $1 sensors are not useful for positioning and navigation on these devices; this is done using the GPS receiver.

All systems perform well when GPS is readily available. However, accuracy degrades significantly when GPS signals are denied—drifting up to 1 nautical mile (1.8 kilometers) per hour for navigation grade to greater than 100 nautical miles (185 kilometers) per hour for tactical grade systems.

Most tactical and navigation grade systems integrate inertial sensors, GPS, and other navigation sensor technology using Kalman filter estimators. For a broad set of missions, operation in a GPS-denied environment requires organic platform-level timing and

19. R. Lutwack, "The Chip-Scale Atomic Clock—Relevant Developments" (2009), IEEE Frequency Control Symposium, pp 573-577.

20. This technology was transitioned by Symmetricom to the SA.45s, which is a 120 milliwatt, 35 gram, 16 cubic centimeter atomic clock with a unit price of approximately $2,000. Commercial information available at time of press at http://www.symmetricom.com/media/files/downloads/product-datasheets/DS_SA.45s_CSAC.pdf

21. Defense Advanced Research Projects Agency, *Integrated Micro Primary Atomic Clock Broad Agency Announcement* (DARPA-BAA-08-32, April 21, 2008).

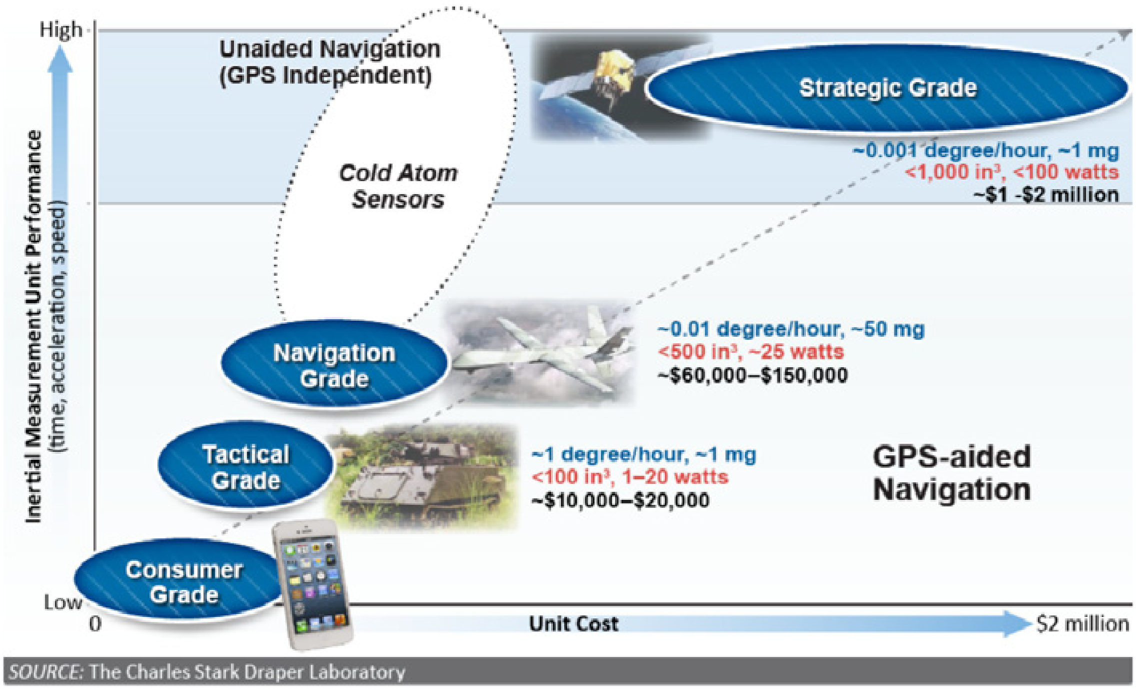


Figure 3 Current Performance and Cost Landscape for Inertial Measurement Units.

navigation solutions. In these situations, strategic grade inertial navigators, which utilize high-accuracy inertial instruments, must be employed. Currently, these instruments are used in only the most critical and demanding missions due to the high cost of the inertial measurement units—between $1 and $2 million per unit. Highly accurate, low cost inertial sensors would significantly change this situation.

Precise navigation for military applications depends on success in addressing two technology challenges: integration algorithms that compute navigation solutions and navigation sensor technology. Efforts underway to develop algorithms and architectures include DARPA's All Sources Positioning and Navigation program, which is projected to provide mature capabilities to rapidly integrate and reconfigure multisensor navigation systems by 2030.[22] Vision-based navigation systems are also beginning to mature, but are currently limited in their utility by the lack of robust algorithms that can simultaneously develop a map of the environment and keep track of the user's position on that map. As these technologies mature, available large-scale, geo-referenced imagery, such as Google Earth, can be integrated into navigation systems.

22. Defense Advanced Research Projects Agency, *All Sources Positioning and Navigation Phase 2 Broad Agency Announcement* (DARPA-BAA-12-45, June 11, 2012).

Quantum Sensor Technology

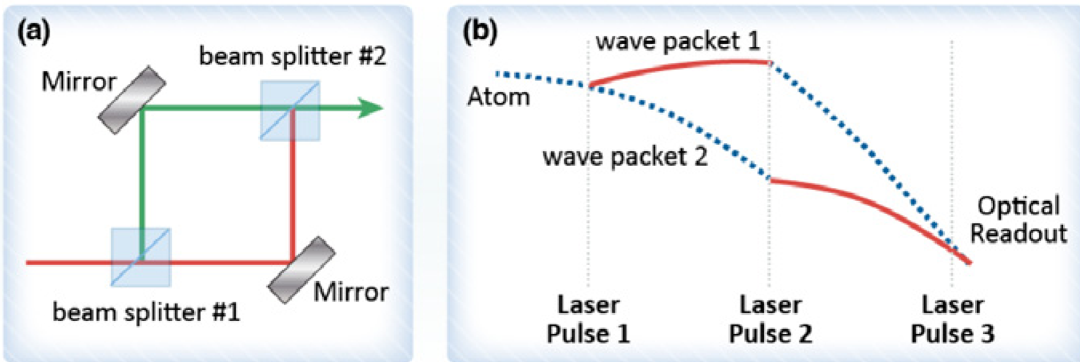
For navigation sensors, a promising area of research and development for GPS-independent navigation is in the area of quantum sensing and atom interferometry. This new class of sensors utilizes a cloud of laser-cooled, extremely cold atoms, and a method to measure their trajectory that can signal the acceleration and angular rotation of the host platform.

The scalability of quantum sensing makes it attractive to a very large range of applications spanning tactical through strategic grade performance. Over the past decade the development of quantum sensing interferometers for inertial navigation applications has made promising strides, and now appears poised as a disruptive technology for strategic grade navigation sensors. Advances in component technologies are expected to enable strategic grade cold atom inertial measurement units to be produced at a unit cost of approximately $25,000. Thus, quantum sensing has the potential to provide a game-changing capability in long-endurance undersea and airborne missions that is otherwise unachievable.

Cold atom interferometers use a cloud of several million alkali atoms as a disposable proof mass. To create this, the atoms are cooled to around ten millionths of a degree Kelvin in a high vacuum environment. They are then trapped by a combination of lasers and magnetic fields. When a sufficient number of atoms are cooled and trapped, the lasers and magnetic fields are turned off and the cloud of atoms is free to move within the vacuum chamber. Next, a sequence of three laser pulses, spaced one millisecond apart, measures changes in their position.

In an optical interferometer (shown in Figure 4a), a laser beam travels through beam splitter #1 and is split into two paths, as represented by the red and green beam traces. After each path is reflected off a mirror, the beams are overlapped again through a second beam splitter. The beams interfere, and for a perfectly static configuration, the interference pattern measured at the output of the second beam splitter will also be static. However, if the entire apparatus were to undergo rotation, light in the red beam path would traverse a different distance than the green beam path, resulting in a change in the total output beam intensity proportional to the rotation rate.

In an atom interferometer, carefully constructed pulses of laser light split a cloud of atoms into two quantum wave packets (labeled 1 and 2 in Figure 4b) that travel along different trajectories. The first and third laser pulses in the atom interferometer sequence act like the first and second beam splitters in the optical interferometer, while the second laser pulse acts like a mirror. In this way, the laser pulses record the atom cloud at well-defined times. Comparing the measurements produces an atomic interference pattern of the cloud and reveals how the cloud has shifted. Because the timing between pulses is well-controlled, the information can be directly translated to an inertial input.



SOURCE: The Charles Stark Draper Laboratory

Figure 4 Comparison between (a) Optical Interferometer and (b) Cold Atom Interferometer.

Atom interferometers can achieve performance beyond strategic grade measuring both acceleration and rotation, and often in volumes much smaller than competing instruments. Moreover, because their operation relies on an optical wavelength stabilized to an atomic transition and an atomic proof mass that is naturally isolated from the environment, they tend to have very good long-term bias stability. This level of performance can be achieved only through the use of quality optical and electronic components and carefully timed measurements. The frequency, intensity, polarization, phase, and duration of the laser pulses must be carefully controlled for high performance measurements.

Today, several high performance atom interferometers have been demonstrated. Laboratory instruments have demonstrated gyroscopes with angle random walk as low as 3×10^{-6} degrees per the square root of time in hours and accelerometers with geophysical accuracy of 10^{-9} g, where g represents the force of Earth's gravity. These successful demonstrations are due in part to advances in critical enabling technologies, such as solid state lasers, vacuum packaging methods, and high performance electronics.

The technology has been shown to be scalable, with the same basic design producing beyond strategic performance with increasing device volume. It is worth noting that these technologies have benefited other atom-based sensors, including atomic clocks and atomic magnetometers. Moreover, many of the technologies and techniques that benefit atomic sensors can be useful for demanding problems in quantum computers and quantum cryptography devices.

Much of this progress has been made under two DARPA programs, the Precision Inertial Navigation System (PINS) and High Dynamic Range Atomic (HiDRA) sensor

programs.[23] Substantial work remains, however, and future development efforts must be coordinated across multiple programs to realize maximum return on the government's investment.

Technology Impact

When manufactured in large quantities, cold atom inertial measurement units have the potential to perform beyond strategic grade at tactical grade costs, while simultaneously realizing significant reductions in size, power, and weight. This advance has the potential to shift the paradigm for weapon system mission accuracy, thereby enabling a host of missions that are currently unachievable.

The study anticipates that with advances in mini-optics and micro-optics, compact lasers, and vacuum technologies, the essential device components for a single cold atom inertial sensor could cost on the order of $10,000. When fully developed, using automated sensor characterization and calibration methods, the cost of a strategic-grade cold atom inertial measurement unit could be reduced to approximately $25,000. This is on par with current prices of tactical grade systems.

These projected unit costs will be achievable only for sufficient production volumes. Strategic devices for Air Force missile programs and Navy navigators account for roughly 1,000 units. Cruise missile programs could account for another 5,000 units, and military and commercial aircraft along with unmanned platforms could present a need for roughly 15,000 units. Systems for longer mission times and greater ranges could represent a market for another 10,000 units, and there are likely to be additional commercial applications that are not currently anticipated. Collectively, the demand could approach 20,000 to 30,000 units, a quantity sufficient to justify the approximately $300 million development investment estimated for a manufacturable cold atom inertial sensor.

A significant mission class enabled by strategic grade navigation accuracy is long-endurance operations in a GPS-denied environment. The current DARPA Chip-Scale Combinatorial Atomic Navigator program seeks to enable 20-meter navigation accuracy for such missions with a maximum GPS outage of 20 minutes, in a packaging volume of 20 cubic centimeters—roughly half the size of an iPhone.[24] Table 3 illustrates the error parameters for such a system, along with corresponding parameters for a more aggressive system that would allow GPS-denied operation for 60 minutes. Both sets of performance specifications are beyond the capabilities of current strategic grade systems,

23. M.A. Suriano, "Robust Technology to Augment or Replace the U.S. Reliance on the Global Positioning System," Research Report, Air War College, February 16, 2011.

24 Chip Scale Combinatorial Atomic Navigator Broad Agency Announcement (DARPA-BAA-12-44, April 16, 2012).

Table 3 Increased Requirements to Achieve 20-meter Accuracy for 60-minute Missions

	20 minute mission[a]	60 minute mission[b]
Accelerometer bias	3 μg	0.3 μg
Accelerometer velocity random walk	50 μg/Hz$^{1/2}$	10 μg/Hz$^{1/2}$
Gyroscope bias	1,460 μdeg/hr	55 μdeg/hr
Gyroscope angle random walk	630 μdeg/hr$^{1/2}$	40 μdeg/hr $^{1/2}$

[a] Target for the Chip-Scale Combinatorial Atomic Navigator (C-SCAN) program
[b] Requirement for a typical anti-access, area denial mission

and both represent significant engineering technology challenges. In both use cases, the most difficult specification is gyroscope angle random walk.

While achieving the target gyroscope performance specifications for the 20-minute mission are expected to be challenging yet feasible, the specifications become substantially more challenging for the 60-minute mission if the packaging volume constraint of 20 cubic centimeters (1.2 cubic inches) is maintained. However, relaxing the volume constraint to 1 cubic liter (~64 cubic inches) will ease the problem. By trading off the relationship between the angle random walk and the device size, a range of cold atom sensor performance may be realized repackaging the same component technologies with different sizes of the vacuum cell and sensor optics. This strategy could provide better than strategic-grade performance for a range of navigation systems.

Enabling Technology Areas

Substantial work remains to establish a producible, affordable cold atom inertial measurement unit. Specifically, engineering advancements are required in four enabling technology areas:

1. **Laser sources.** Compact, low power, high performance, rugged lasers are required to perform atom cooling and trapping as well as optical manipulation and readout. An achievable program goal is to reduce the current size of 2,000 cubic centimeters by 1,000 times, reduce the current power draw of 100 watts by 500 times, while maintaining the 100 milliwatt optical output using narrow line vertical-cavity surface-emitting laser or other short cavity laser technology.
2. **Low power vacuum technology.** Cold atom sensor operation requires low vacuum levels, on the order of 10-8 torr, to prevent collisions between cold atoms and background gas molecules. An achievable program goal is to reduce the weight and size of current pumps from 10 kilograms and 2,500 cubic centimeters to 100-

milliwatt vacuum systems that use low helium-permeable glasses bonded to metallic chip substrates and do not significantly contribute to sensor volume or power.

3. **Mini- and micro-optics.** Compact optical systems featuring high efficiency, minimal aberrations, and good phase front purity are required to produce optical beams with the appropriate characteristics. An achievable program goal is to reduce current table-top optics footprint from 1,000 cubic centimeter to less than 10 cubic centimeters using monolithic construction methods for built-in device stability.
4. **High efficiency electro-optics.** Devices that efficiently shift optical frequencies and produce brief optical pulses—less than 5 microseconds—are needed to conduct atom cooling, trapping, and inertial measurement sequences. An achievable program goal is to reduce the volume of devices from 20 cubic centimeters by a factor of 10, and to reduce the power from 1-watt crystal-based devices by a factor of 100.

RECOMMENDATION 3

DARPA expand and focus its investment in key cold atom components with the objective to create low-power, small volume, affordable components with the maturity to support a production program for advanced inertial measurement units

- An additional $40 million per year for five years is recommended.
- A hardware development program for an inertial measurement unit is recommended in parallel with this investment. This program should emphasize affordability and producibility to yield game-changing navigational capabilities.
- Air Force and Navy (through their R&D organizations) should collaborate on a program to develop and demonstrate an affordable, producible cold atom inertial measurement unit capable of maintaining unaided 20-meter accuracy for 60 minutes.
- The size, weight, and power should be selected based upon a systems engineering effort that considers applicable missions, scenarios, and operational concepts.
- Experience indicates that such complex hardware development programs typically require on the order of $100 million and take 7 to 10 years to transition today's conceptual instruments to a production of a modern design.
- To ensure the program tracks mission needs, a prototype unit should be available for test and experimentation after the first three years.

Networks Inherently Self-defensible to Cyber Attack

At present, there are no known ways to fully protect cyber systems from malicious intrusion and potential damage or theft. Within the next decade, a number of well-attended and funded technologies and protocols are emerging and may be developed to significantly mitigate this problem. However, a near-term solution was identified in this study that may be useful for some focused and narrowly defined systems. A near-term demonstration project is proposed for a system architecture comprised of digital processors, data storage, and networks that is inherently self-defensible from cyber attack.

The proposed approach capitalizes on the fact that there are some critical infrastructure systems that have a unique set of characteristics that make them easier to defend. These systems include control systems for power grids, municipal water supplies, and air traffic control, and for some defense communication and mission command systems. While trust and availability of these systems are critical to national security, they tend to be less complex with moderate data transmission rates and the ability to withstand built-in microsecond delays to inputs and outputs.

The proposed solution uses a hardware chip to monitor the operation of the software operating system, regularly ensuring operating system software has not been modified. Because malicious modification of operating system software is the primary attack vector for cyber intrusions, compromising a system protected this way would become much more difficult and expensive. Creating trustworthy systems and periodically refresh it will force attackers to confront a moving target. The proposed approaches would make it more difficult and resource intensive for both external and insider attackers to successfully attack cyber systems.

Protecting National Critical Infrastructure

It is well known that U.S. infrastructure is vulnerable to cyber attack. This includes power grid control systems, internet and communication systems, financial systems, and the air traffic control system networks. Most of these systems today are protected by some defenses, and offensive deterrence is an option in some cases. The optimum protection capability for these systems would be self-identification of an attack and a response in real time. However, identification of attack and effective response requires action as fast as—or faster than—the system operates.

This approach does not address all vulnerable systems. Financial systems and commercial internet traffic, for example, require very high data rates and persistent connectivity to the commercial internet. Corporations that operate these systems must plan for many vulnerabilities, including cyber threats, and they cannot afford to invest in fully

resilient systems to counter every risk while remaining competitive. When driven by business needs, these companies are highly motivated to find a solution and implement it without bureaucratic delays necessitated by government involvement. The current situation, however, has not yet generated a sense of urgency within many private corporations to invest in this level of capability.

If many such systems were to fail at the same time across critical commercial systems—banking, communications, power, and so on—national security could be threatened. An evolving national policy issue is to create incentives for the private sector to collectively invest in capabilities to protect systems that they individually do not protect today. The government can also help develop cost effective technologies. This proposal is one step toward such technologies.

Protecting Networks and Weapons Systems

Cyber attacks on national security networks and databases are regularly detected.[25] While most attacks are low-level with intent on financial gain or minor mayhem, many are from nation states acting as adversaries to the United States. A key element of resilient battle management is the ability to withstand cyber or electronic warfare attacks and to respond in a timely manner. This is particularly important for systems involved in the operation of critical infrastructures or homeland defense.

The task force believes a solution exists to protect critical functionality in a restricted class of systems. Such a capability would block intrusions in real time and ensure operating systems continue to perform in their original configuration. Systems would cue the operators to an attack and restore the systems and databases to a trusted state. As with any military capability, such an approach will give rise to countermeasures and counter-countermeasures. However, because this solution is based in trusted hardware, physical access to each target site would be needed to attempt to compromise the system. If properly implemented, this capability could prevent wide-scale attacks and avoid a cyber war before it starts.

Example Critical Systems That Could be Protected

Systems with better ease of implementation are those that have relatively low data rate requirements, which only pass data rather than executable code over the network, and which are amenable to having software updates done via a two person protocol with physical access to the device. Electric power grid control, for example, requires very low

25. Defense Science Board, *Resilient Military Systems and the Advanced Cyber Threat* (2013). Available at time of press at http://www.acq.osd.mil/dsb/reports/ResilientMilitarySystems.CyberThreat.pdf

data rates and the data has a number of fixed formats so that incoming packets can be checked to insure that they are valid data that will not harm the system. Power grids operated by the Department of Defense could impose the requirement for the physical presence of two persons to implement a software update. Conversely, systems such as Link-11, Link-16, and commercial satellites need high data rates and the capability to pass both data and executable code over the network.

The impact of increasing the cyber resiliency of a system was estimated by considering two factors: the extent that operation of the system is affected by these additional constraints, and whether a compromise affects all missions or a subset of missions. The higher potential impact cases were broadly used systems that may be more amenable to the constraints imposed by the proposed security regimen. Example critical systems that may be appropriate for this approach are the U.S. power grid, made up of generation, transmission, and distribution systems. Also included are air traffic control, water distribution, and certain centers in industries such as petroleum and chemical processing. Selected defense command systems may also be appropriate.

A survey of systems with defense dependencies reveals a wide variety of systems with different degrees of difficulty to protect and different levels of impact if they are compromised, as shown in Figure 5 and described in Table 4. The study identified the systems in the shaded area to benefit most from the proposed approach.

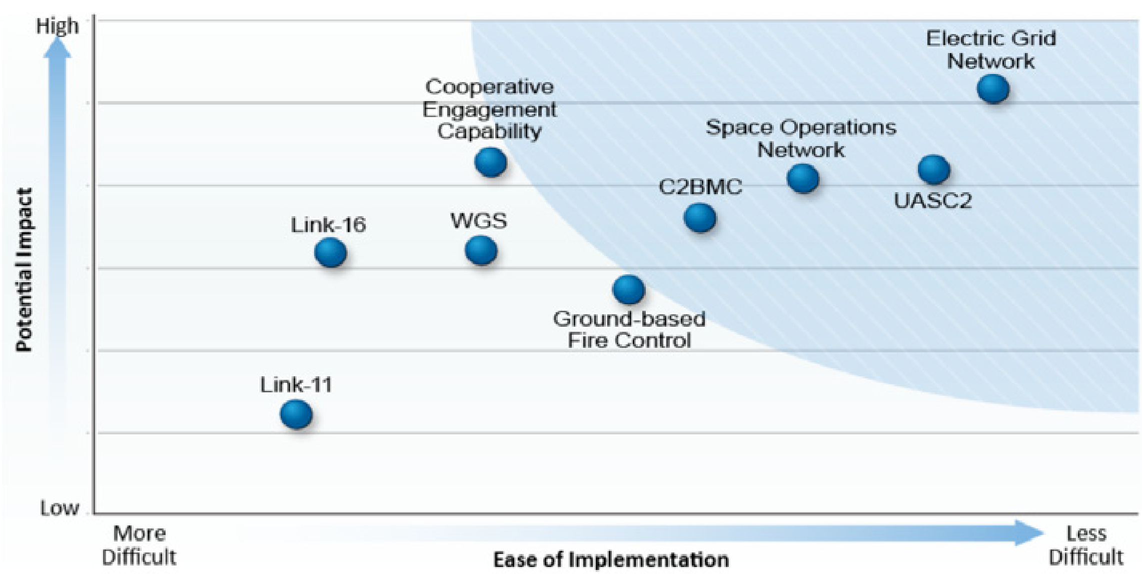


Figure 5 Potential Impact and Ease of Security Enhancement for Some Critical Systems Important to Defense Operations.

Table 4 Candidate Networks for Security Enhancement

Candidate System	Description
Electric Grid Network	The U.S. electric grid is a complex network of independently owned and operated power plants and transmission lines. Aging infrastructure, combined with a rise in domestic electricity consumption, has forced experts to critically examine the status and health of the nation's electrical systems. While some defense bases have their own power supply and many have temporary generator support for some critical systems, all defense bases are dependent on the power grid.
Unmanned aerial system command and control (UASC2)	An unmanned aerial system mission command is a software and interface. The government has the source code to the unmanned aerial system framework, owns the open and documented interfaces, and makes them readily available for vendors to adapt and compete to provide the latest innovative ideas and applications.
Joint Space Operations Network	The Joint Functional Component Command of Space, through its Joint Space Operations Center detects, tracks, and identifies all man-made objects in Earth's orbit. It tasks the space surveillance network, a worldwide network of 29 radar and optical telescopes, both military and civilian, to observe the objects.
Command, Control, Battle Management, and Communications (C2BMC)	C2BMC is the hub of the Ballistic Missile Defense system. C2BMC globally links, integrates, and synchronizes individual missile defense elements, systems, and operations. Through its operational software and networks, the C2BMC program provides redundant connectivity and enables on-site operations and sustainment for global combatant commanders.
Wideband Global Satellite (WGS) Communications System	Wideband Global Satellite (WGS) communications system is the highest-capacity satellite communications system in the Department of Defense. Each satellite can route 2.1 to 3.6 gigabits of data per second, providing more than 10 times the communications capacity of the predecessor Defense Satellite Communications System III satellite.
Cooperative Engagement Capability	Cooperative Engagement Capability is a real-time sensor netting system that enables high quality situational awareness and integrated fire control capability. The system is designed to enhance the defense capability of ships and aircraft by the netting of battle force sensors to provide a single, distributed defense capability. The system enables integrated fire control to counter increasingly capable cruise missiles and manned aircraft.
Ground-based Fire Control	Ground-based fire control employs communications systems and ground-based interceptors that are capable of detecting, tracking, and destroying ballistic missile threats by utilizing multiple sensors.
Link-16	Link-16 is the Department of Defense's primary tactical data link for command, control, and intelligence, providing critical joint interpretability and situation awareness information. This tactical data link is used by the U.S. Navy, joint services, some nations of the North Atlantic Treaty Organization, and Japan. Link-16 uses the Joint Tactical Information Distribution System for its communications component.
Link-11	Link-11 employs netted communication techniques and a standard message format for exchanging digital information among airborne, land-based, and shipboard tactical data systems. Link-11 provides high speed computer-to-computer digital radio communications in the high frequency and ultra-high frequency bands among ships, aircraft, and shore sites with access to the Tactical Data System.

Elements of Technologies and Protocols

The proposed solution is applicable for systems with relatively low data rates, on the order of megabytes per second, and requiring infrequent updates to the software operating system. The concept involves hardwiring a *gold standard* of the operating system software into a coprocessor that monitors system operation on a regular basis. If at any time the operating system software on the main processor does not match that on the coprocessor, the coprocessor reloads the gold standard onto the main processor, restarts normal operation, and notifies the operators that the main processor software was compromised. Such checks and restarts could take place thousands of times a second, making it very difficult for an adversary to successfully gain malicious access to the system.

Additional defensive techniques could be applied to raise the defensive posture of the system even higher. Data links could be encrypted and screened to remove executable code, with each encrypted link inspected, for example. If a packet fails inspection, it would be immediately discarded. Note this process may result in small time delays, on the order of one microsecond, and systems must be able to tolerate this delay.

Processors in such a system could be designed to support isolation of separately executing programs, thereby ensuring that one program cannot affect the execution of another. Finally, cryptographic keys could be stored without permitting those keys to be visible in processor registers or memory.

Such functionality is available today in commercial processing units and chipsets that use trusted platform modules and that support hardware virtualization.

Secure Hardware and Software Environment

The tradeoff to gain this higher level of security is the loss of the efficiency gained from remote provisioning. One of the benefits of networked systems is the ability to update installed systems around the world in real time, as is widely used for cell phones applications and laptop antivirus software. While highly efficient, this is also the main reason cyber attacks can be so damaging: they can scale very quickly and require few resources.

The proposed concept breaks that paradigm by requiring new hardware to be physically installed at every processing point in the system. For a large power grid, that could require a hundred touch points to update a system. Therefore, this architecture is only practical for systems whose critical operation outweighs the economic efficiency lost through the upgrade process.

Critical software would be built and maintained using methods that increase confidence that it is free of flaws. Most importantly, the reliance on trusted hardware

means the coprocessor creation and installation must be protected from attack. To defend against attacks on the supply chain, the components critical for security should be produced at independent trusted foundries. Computing systems should be packaged with sufficient shielding and tamper detection to preclude physical attacks. Finally, physical security to install it in the field would also be necessary, such as requiring two persons for any component replacement.

Demonstration Projects

Demonstrations can provide the means to evaluate and improve architectures for digital systems that are self-defensible against cyber attack. Two demonstrations are proposed for a power grid application and for a defense control system.

The biggest concern for these demonstrations is the potential for a large false positive rate. To address this, the study strongly recommends that the implementation team resist making the solution more complex or adding additional constraints and conditions. Simplicity, ease of implementation, and the ability to verify the application are the strengths of this approach.

RECOMMENDATION 4

USD (AT&L) task DARPA to lead two self-defensible cyber security demonstrations to demonstrate networks inherently self-defensible to cyber attack.

- The ground control system for missile defense may offer a useful defense mission command system for demonstration.
- A SCADA system with stable, long-lived executable software systems and limited, low-bandwidth requirements is a useful demonstration. A defense infrastructure electric power grid case offers the challenge to control a distributed system with significant physical nodes. The power plant at Warner Robins Air Force Base offers a good opportunity to demonstrate the power grid application within the Department of Defense. Systems at the Department of Energy Idaho National Laboratory may also be a suitable demonstration site.

Each test case should be subjected to a red team adversary attack led by the National Security Agency. All involved should be aware that implementation of this recommendation may surface better demonstration candidates, and should maintain flexibility. Finally, when the task force discussed this approach with technical experts, the experts tended to expand the types of eligible systems thereby reducing or even voiding the capability offered by the simplicity of the idea. The power of this approach is its simplicity which must be maintained.

3 Key Investment Opportunities to Achieve Superiority through Cost-imposing Strategies

As a complement to developing increasingly capable, complex, and costly systems for maintaining capability superiority, the study recommends that the Department think about ways to change the balance of cost in the U.S. favor by developing capabilities that are more expensive for the adversary to counter than for the U.S. to deploy.

Conventional, Affordable Effects at Intercontinental Ranges

The driving rationale for such a capability is to enable U.S. forces to attack deep into the enemy heartland and produce desired conventional effects that cannot be achieved efficiently by current aviation, naval gunfire, or artillery assets. The most critical concern in establishing such a capability is the cost of producing the desired effect, both in terms of personnel and dollars. The value of enemy targets must be considered in the development and deployment of any weapon, as well as the set of targets that can be accessed in addition to those established for more expensive solutions.

Current Technology

Existing bomber and missile systems that have desired long-range conventional strike characteristics are very expensive, limited in fleet size, and must also be precisely maintained to achieve desired effects. These systems have a nominal range of 3,000 nautical miles (5,500 kilometers), the potential striking power of a 1,000 pound bomb, and delivery accuracy of 1 to 3 meters. The weapon effects are not in the class of weapons of mass destruction, and are compatible with extant policies and international agreements.

Of course, the criticality of time-to-target is an important consideration because many key targets might be mobile or fleeting. The capability of prompt global strike, where *prompt* means a flight time of approximately one hour, has been found to add substantial cost to a system. Further, the difficulty of locating and tracking such targets significantly complicates the warning, target acquisition, tracking and engagement functions demanded of such weapons and their support infrastructure.

Hardened or deeply buried targets, such as some key mission command facilities, can be attacked with weapons of mass destruction or high momentum penetrators. Those weapons, however, could be subject to existing treaty limitations, cause collateral damage, fail to

achieve sufficient battle damage, and could be much more expensive than a weapon designed to be useful for most targets or missions.

Desired Technology

The study identified the need for a low-cost conventional weapon able to strike important weapons, sensors, facilities, and infrastructure targets. A specification for attack at 3,000 nautical miles within ten hours was found to be reasonable for most missions and would have significantly less impact on cost than more prompt response scenarios. The task force believes it is reasonable to set a firm cost target for a system that could provide the desired effect. Within these parameters, it was estimated to be no more than $2 million per munition, assuming a procurement quantity of several thousand units.

Required characteristics begin with a simple, modular design with the ability to launch a precision attack in less than three minutes, from ground, air, or sea launch. It would deliver a Joint Direct Attack Munition (JDAM) type warhead, with blast and fragmentation effects and limited target penetration capability. It could operate in degraded GPS or electronic warfare environment with robust situational awareness. The design would also integrate commercial or government off-the-shelf components for propulsion, sensors, and communications.

Concept of Operations

The system would be designed to complement strategic prompt global strike capability. Because it could be produced at far lower costs, this would allow adequate numbers of weapons to engage multiple targets simultaneously, saturate enemy countermeasures, and screen penetration or operation of manned and other unmanned systems. It would not be as precise as some more costly systems, but instead trades a higher probability of detection and somewhat larger vulnerability for cost. Preliminary sizing of the system indicates a 500 to 700 kilogram (1,000 to 1,500 pound) vehicle.

Several notional system concepts were evaluated. They included all system options that were determined to be deployable prior to 2030.

The first option was the deployment of special operations forces, which can be very precise, have the highest flexibility, can perform very effective bomb damage assessment, can loiter until the target is more clearly defined, attack for the optimal effect, and conduct follow-on missions. Unfortunately, the risk of casualties, slow response to the order to attack, and requirement for protective sensors and weapons, as well as any unique assault weapons, and very difficult insertion and recovery challenges, made this

option unacceptable. Finally, special operations force approaches are not scalable to a large number of targets.

The next option was the use of ballistic missiles, which are unmanned, relatively low risk, very responsive, able to rapidly execute the mission, able to hit mobile targets, able to carry a very large conventional warhead, able to carry a penetrator for buried targets, amenable to existing launch facilities and mission command, and minimally dependent on forward deployment. Unfortunately, the ballistic missile has issues with launch ambiguity, flexibility, overflying allies, and cost-per-round. Such weapons also offer problems for human interaction during the terminal phase of the mission because of the very short time for such interaction before the weapon re-entry causes a plasma blackout of the data link. The sophistication of launch, guidance, and aerodynamics of the vehicle make the ballistic missile very expensive, and the number of long range ballistic missile platforms is limited by strategic arms agreements.

Another option was the use of cruise missiles, which are unmanned, relatively low-cost, easily connected for human interaction, highly maneuverable, able to be employed like aircraft, forward deployable, and compatible to air, sea, or ground launch. Unfortunately, the cruise missile is low speed, less survivable against air defenses, presently limited in range for an effective payload, and potentially affected by policies limiting the production of platforms which can deliver weapons of mass destruction.

The final option was directed energy weapons, which are inherently the most precise, most rapidly responsive, able to provide varying levels of lethality, and able to simultaneously be a sensor, illuminator, and weapon. However, directed energy weapons have the highest level of technical risk, are ineffective against relatively simple countermeasures, require significant R&D, and are very expensive—although the ammunition is very inexpensive.

Based upon an assessment of these options, the study decided that, including the limitations identified in the options review, the cruise missile was the most effective weapon option for achievement of the desired capability at the required cost.

Cost as an Independent Variable

Having selected the cruise missile as the best generic weapons option, the study established firm systems requirements that centered on cost-per-mission, *i.e.*, cost-per-cruise missile or missiles necessary to achieve the desired effect. A simple modular design should be emphasized that exploits the use of government and commercial off-the-shelf technologies, with state-of-the-art subsystems and lower risk, existing technologies. In this way, both technical and production risk will be reduced and system cost drivers will be identified.

A set of conceptual designs will be established and evaluated. These designs will emphasize cost to achieve the desired effect. As is often the case, threshold and objective requirements will be evaluated, but only if necessary. Since the set of requirements appears to have a wide degree of flexibility, a block approach should be optimal. For example, a variant of each desired capability below can generate the investment needed for a successful system:

- Launcher: air, sea, or ground
- Time to target: from approximately 10 hours to days
- Weapon effect: blast, fragmentation, penetration
- Cost: less than $2 million, at quantities greater than 1,000 systems

The block approach would allow an evolutionary increase in capability and continuous improvement of cost.

Achieving the cost requirement is preeminent to the success of this program. This cruise missile will be much more cost effective if it is acquired in large numbers. It will be bought like an ammunition system, and the key to the system solution will be effective and efficient production of each lot (or block, as appropriate) of ammunition.

Benefits of a Large Production Quantity

Based on the relatively low cost of the tactical cruise missile, the U.S. weapons concepts of operations can be modernized in accordance with a different philosophy: that quantity has a quality all its own. It will be interesting to determine whether large quantities of airborne weapon systems could be produced in the same way, and at the same costs, as large quantities of ammunition are produced today.

Owing to its concern for the safety of crewman and survivability of each platform, the U.S. military has developed and produced systems, which are primarily flexible and sophisticated. This strategy leads to very high cost solutions and, thus, very small inventories. The Military Services prefer the inherent advantages of human operation even in scenarios of high risk to the operator. An enduring consideration is the relationship between the vulnerability of the weapon and the need for a human operator.

Remotely piloted aircraft systems, such as Predator, have proven their worth, but the application of remotely piloted aircraft to conduct attack missions is typically limited to scenarios with inherently low chances of collateral damage and a permissive airspace.

A low-cost, long-range weapon could be tasked to accomplish missions that are now assigned to more sophisticated platforms. For example, sophisticated interceptor aircraft protect ingress and egress for attack aircraft. A cruise missile acting as a decoy would allow

more capable strike systems to accomplish more difficult missions, or to make those systems more survivable. A few inexpensive cruise missiles could act as a deep-strike precursor and destroy air defense sites, so that a manned attack aircraft could more successfully penetrate enemy airspace. Also, a large flight of inexpensive cruise missiles, with signatures resembling manned aircraft, could saturate enemy air defenses, confuse enemy surveillance assets, strike many targets, and cause enemy commanders to make uninformed decisions. This approach could cause the enemy to invest large numbers of sensors and platforms to intercept such targets, reducing the vulnerability of U.S. manned systems.

Technical and Production Risk

The design and engineering of low-cost versions of such military systems has received little attention, although the long extant techniques used in manufacturing ammunition and the new techniques of low cost manufacture, like 3D printing, should make such systems feasible. Also, when the American military demonstrates a commitment to fewer, more technically sophisticated platforms, an enemy can tailor countermeasures accordingly. For example, each enemy air defense site can be provided a relatively small inventory of sophisticated weapons, focus on counterstealth, employ electronic countermeasures, and establish centralized mission command. The use by the U.S. of large numbers of simple platforms could drive the enemy to invest significant resources and change its operational and materiel strategies.

Production cost drives the feasibility of such a system, and cost will be the determining factor in the decision to procure the weapon. Such cruise missile systems must be considered to be a tactical weapon, with remote human interaction, and a large conventional warhead. The terminal guidance system must achieve high accuracy using an airframe and aeronautical structure, which provides the necessary lift, drag, and signature characteristics. Propulsion should include a low-cost, high-endurance turbine engine subsystem that enables the weapon system to achieve intercontinental range (albeit subsonic) and accomplish its mission within a reasonable time envelope. The system should also have a significant loitering capability for shorter-range scenarios. While loitering, this extra endurance can allow the system to be a surveillance and reconnaissance surrogate, as well as a cruise missile. Ground, sea, and air launch variants should be evaluated, and every effort must be made to achieve best value with a common design. The multirole capability will ensure that all avenues for maintenance of a global deep strike capability are enabled.

Can the requirement for this system be satisfied by either a small diameter bomb or air-launched cruise missile? The small diameter bomb, which costs only $40,000, can be delivered by a variety of fighters as well as bombers. Unfortunately, it must be delivered within 100 kilometers of the target, and is less accurate and less lethal. The conventional

alternatives based on an air-launched cruise missile have been retired, but the production experience will contribute to a lower risk in development and acquisition of similar weapons. The conventional variant of the air-launched cruise missile (with a cost of approximately $1 million) has a range of approximately 700 kilometers. The nuclear variant of the air-launched cruise missile has a range greater than 1,500 nautical miles, can be refitted with blast, fragmentation, and target penetrator warhead variants, and can carry payloads as heavy as 3,000 pounds (1,360 kilograms). However, the venerable B-52 aircraft is the only platform capable of launching it, and the missiles are also out of production.

Policy Issues

In 2007, the U.S. Air Force announced its intention to retire its advanced cruise missiles, which was a modernized air-launched cruise missile with less capability. The air-launched cruise missile fleet was also reduced by more than 500 systems, leaving 528 nuclear missiles. Reductions were a result of the Strategic Arms Reductions Treaty that required fewer than 2,200 deployed nuclear weapons by 2012. In 2012, the Air Force announced plans to extend the life of air-launched cruise missiles until 2030, and it will award contracts for development of a replacement long-range stand-off weapon in 2015.

The policy implications of deploying an intercontinental, precision cruise missile with a capacity to carry relatively heavy payloads are significant. Development of such a system is unhindered by existing international agreements, but the production and deployment of such a system is problematic. One can understand the concern of treaty partners, especially since it is the recommendation of this study that thousands of these systems be produced. Unless a strategy can be developed, which proves that such a system is not potentially a nuclear delivery vehicle, the system concept may need to be modified. Successful system deployment options might require reducing range, payload, or quantities—any of which might cause the concept to be unacceptable to the Department. An accommodation that would allow inspection by treaty partners who could verify the loads carried by conventional systems is possible.

Program Management and Coordination

A fast-moving ubiquitous technology future challenges the United States' ability to maintain superior war fighting capability with a significantly reduced budget. Achieving this desired end state requires that cost, performance, missions definition, concepts of operation, and adversary advancements must be continually traded to achieve the most capability for the money spent. Learning to operate in this framework requires that changes are necessary in the methods used to develop and deploy integrated war fighting capabilities.

This program should form the basis of an experiment to identify an alternate approach to system development. Fundamental to this approach is a management leadership team that is charged with a cost target that defines program success and includes a program office, representatives from the combatant commands and Military Services, two or three contractors, test community experts, a missions analysis simulator specialist, and a red team that assures the validity of the trades and adversary capabilities.

The management team should be charged with achieving the cost, capability, and mission success trades by following the program flow shown in Figure 6. During the first three months, the team should perform trade studies that truly weigh cost equal to performance with contractors tasked to generate conceptual designs, along with realistic cost projections. These studies will be evaluated by a mission simulator supplied, maintained, and operated by an organization that is independent of the development contractors, possibly a federally-funded research and development center, university affiliated research center, or an independent not-for-profit laboratory.

Three months into the program, conceptual designs will be defined along with a set of cost and risk experiments. Approximately 15 months into the program, a selected design of system, subsystem, and concepts of operation will be incorporated into a technology demonstration phase. At this point, a full set of specifications will be completed that provide the basis for the engineering development, full-scale development, and initial operating capability by 2018. The trades among cost, performance, and mission will

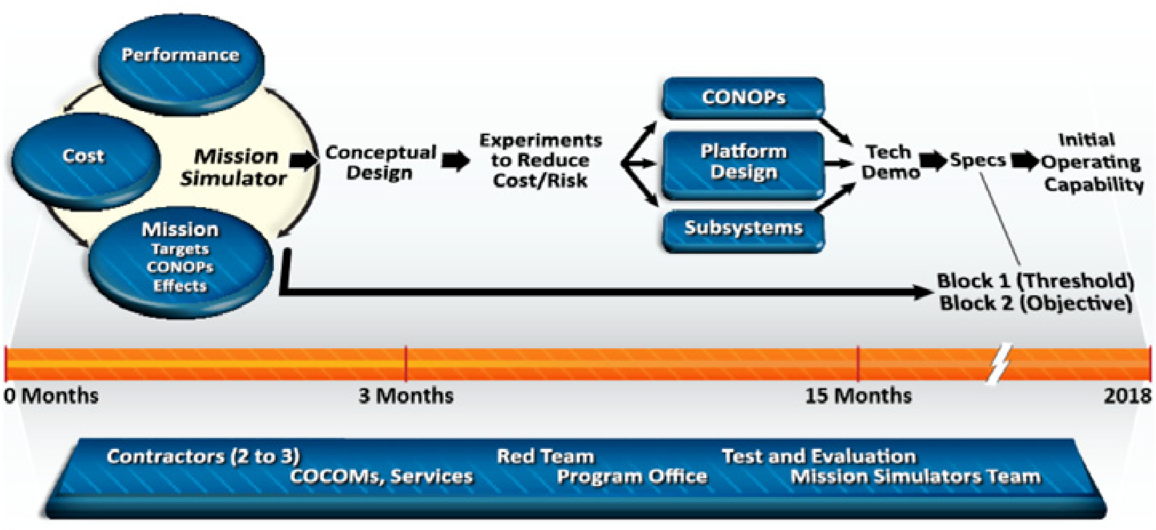


Figure 6 Recommended Implementation Plan for Conventional, Affordable Effects at Intercontinental Ranges

continue throughout the entire program and adjustments will be made to adapt required performance that reflects mission and adversary developments.

Responsibility for the program will be with USD (AT&L) through the technology demonstration phase, at which time the responsibility will be transferred to the appropriate executive agent.

RECOMMENDATION 5

USD (AT&L) evaluate, design, and develop a low-cost conventional weapon concept that costs less than $2 million per round, can support other reconnaissance and attack missions, and strike important weapons, sensors, facilities, and infrastructure targets at ranges up to 5,500 kilometers (3,000 nautical miles).

Long-Endurance, Autonomous, Networked Unmanned Underwater Vehicles

Capabilities and technologies to affordably address undersea threats and supporting infrastructure of a peer-competitor or regional adversary in the 2030 time frame are addressed. An unmet need in that time frame will be an affordable response to the anti-access undersea threat. Against highly capable and very quiet diesel-electric submarines, the baseline U.S. counterforce capability is the nuclear attack submarine, a platform that is an order of magnitude more expensive than its diesel electric adversary. Against a peer-competitor with the economic ability to deploy significant numbers of diesel-electric submarines, and also in the regional adversary context, the proposed concept for a network of low-cost, long-endurance unmanned underwater vehicles will leverage the capabilities of nuclear attack submarines to enable an affordable response to the anti-access undersea threat. Each vehicle is expected to cost, in production quantities, an order of magnitude less than adversary diesel-electric submarines. For effective implementation, an individual vehicle should cost from $10 to $20 million in production.

Unmet Operational Needs

Trends for the 2030 security environment indicate that U.S. Naval expeditionary forces will become increasingly vulnerable to both 20th century diesel-electric submarine and torpedo technology and to 21st century ballistic cruise missiles. In 2030, peer-competitors, as well as lower-tier competitors, will utilize space-borne and terrestrial sensor networks for targeting mobile U.S. forces and will increasingly apply technology to limit access and achieve asymmetric engagement advantages.

U.S. forces will increasingly apply robotics and autonomous operations to supplement capabilities of fewer, increasingly expensive manned platforms and, especially, to reduce casualty risk associated with exposure of manned platforms in missions subject to hostile fire. Presently, unmet operational needs include undersea robotic platforms providing large payload, range, endurance, and survivability to support a variety of undersea missions. Underwater robotic platforms exhibit the capabilities needed to augment the reduced fleet at range and with persistence in contended regions and must be developed with a cost imposing advantage. A networked approach using these lower cost vehicles can enable affordable and significant mission capability in the 2030 timeframe.

Evolving Operational Concepts

It is ironic that 20th century diesel-electric submarine technology continues to maintain a viable challenge to 21st century naval forces while at the same time this low-cost and low-risk propulsion technology is largely overlooked for application to long-endurance power packages for undersea robotic vehicles. Technology updates in higher capacity batteries and more efficient motors from electric automotive applications make the propulsion concept even more attractive. Other options for long-endurance underwater vehicles include fuel cell technologies, and advanced electro chemical and radionuclide decay sources. Additionally, augmenting large diesel-electric unmanned vehicles with very low cost, small unmanned vehicles that utilize wave action for power generation should be considered.

The near-term operational concept consists of self-deployed, networked, autonomous vehicles with sufficient range to enable deployment into and persistent operations within contended littoral and regional waters. To defeat anti-access strategies, payloads could acoustically generate false targets, decoy and spoof undersea surveillance and threats, and assist in the localization of those threats.

Spoofing and the potential for kinetic attack could induce behaviors in peer-competitor diesel-electric submarines, unmanned underwater vehicles, or other underwater systems that significantly degrade elements and functions of the anti-access system, including undersea sensor grids, fixed and mobile nodes, as well as shoreside fixed and mobile military and commercial communications and mission command networks. In general, unmanned underwater vehicles would operate as part of a cooperating squadron of unmanned underwater vehicles with links and synergistic activities orchestrated with larger groups that would involve manned platforms. Inherent communication capabilities and improvements in payload size, weight, and power would facilitate multipurpose capabilities in the 2030 environment.

Capabilities Required

Addressing the undersea threat from diesel-electric submarines, unmanned underwater vehicles, mines, and deployed arrays of these in remote theaters would require the following capabilities:

- Scale and propulsion providing long endurance and long range for self-deployment, persistent operations, and reactive relocation
- Navigation sensors for deep-water navigation
- Long-range communication systems for covert and occasional high bandwidth exchanges
- Mission-level autonomy and tactical situational understanding
- Affordability to enable deployment quantities permitting timely coverage of an operational area and synergistic cooperative activities
- Significant improvements in payload size, weight, and power supporting multiple mission areas such as reactive acoustic spoofing, jamming, and false target generation, with the ability to affect adversary sensing, navigation, and communication systems

Supporting Technologies

Long-endurance propulsion technologies and components can be drawn from the electric vehicle industry. For example, a diesel-electric drive may be paired with mature lithium battery technology. The desired capabilities will require maturity in the integration of these technologies and operational experience in the applications of unmanned underwater vehicles.

The core of long-range underwater capability is accurate inertial navigation. Alternatives include advanced ultralow drift sensors and inertial aiding with correlation velocity loggers evolved for deep-water application. Advanced sensing and communication technologies include long-range acoustics and supporting transducer technologies for acoustic domain spoofing of active and passive sensors on adversary platforms.

Technology enabling mission-level cooperative autonomy is critical. The reliability and performance of mission-level autonomy must be verifiable and readily adaptable to new missions, sensors, and payloads. Signal processing for concurrent active sonars must also be developed and matured to enable cooperative operations of multiple vehicles. Open architecture for platform components, payload components, and software is another key technology for autonomy, control, and payload signal processing.

Block upgrades of new capabilities are envisioned as new sensors and payloads mature and can be integrated within the cost constraints of the system.

Development Plan

Providing operational capability with large, robotic vehicles to augment manned platforms by 2030 will require a program of experimentation and development of equipment, tactics, and mission execution experience. The most effective path is evolutionary, utilizing near-term, large, unmanned underwater vehicle platforms interacting in networks with manned vessels.

A three stage program is envisioned, beginning with development of experimentation, payload, and concepts of operation using existing commercial and research unmanned underwater vehicles. During stage one, existing platforms such as the Proteus (Bluefin), the Echo Ranger (Boeing), the Seahorse (Pennsylvania State University Applied Research Laboratory), and others will be integrated with avionics and mission hardware and used to establish the feasibility of unmanned operations networked with remote manned platforms. The primary capability to be established and demonstrated is the ability to utilize the network to acoustically spoof, jam, and generate false targets to confuse an adversary's diesel-electric submarines and unmanned vehicles in the execution of an anti-access and area denial strategy. Experiments would focus on establishing the performance of mission sensors and networked communications in realistic environments and on development of tactics and software to exploit cooperative autonomy to increase the probability of mission success. A set of graduated milestones for a four-year period of experimentation is envisioned.

Data from stage one experiments would support informed systems engineering trades and performance goals including range, speed, depth, and payloads for stage two. Stage two would utilize lessons learned from stage one experiments to evolve an affordable vehicle and associated avionics and payload components that would enable revolutionary mission capabilities for an initial operating capability in 2020. For this time frame, hybrid diesel-electric propulsion would be a strong candidate to provide necessary range and endurance. Stage two would see the definition of one or several standard large unmanned variants and the beginning of volume production to equip and train squadrons of operational units and supporting infrastructure such as tender vessels. The target for initial operating capability in 2020 would include a squadron that would support enduring operations in major regional theaters.

Stage three would incorporate component technology upgrades and expanded capabilities into future evolutions of the long-endurance, multipurpose, autonomous networked unmanned underwater vehicles; establish tactics, techniques, and protocols for an expanded mission set; and further populate the unmanned underwater fleet, the corps of trained operators, and the supporting infrastructure to address the evolving

threat landscape. The ability to cost-effectively and safely perform missions in the undersea environment using this fleet will become as accepted and commonplace as the current use of unmanned air vehicles.

RECOMMENDATION 6

The Chief of Naval Operations task the Naval Warfare Development Command to begin development of a network of low-cost unmanned underwater vehicle platforms to initially provide acoustic spoofing, jamming, and false target generation.

The Naval Warfare Development Command should establish a cooperative program in conjunction with the Navy Laboratories and the Oceanographer of the Navy to develop the operational concepts for the system and exploit current technology. The program would demonstrate the near-term capability and establish options for block upgrades of new undersea mission capabilities when they are mature while focusing rigorously on achieving the desired cost point for each unmanned underwater vehicle in production at an order of magnitude less than the adversary's cost for their diesel-electric submarines.

Enhanced Vertical Lift

The threat environment of the last three decades has been supported in many missions by the Army's fleet of vertical lift aircraft. While air cavalry weapon support systems and utility support systems have served the country well, they have not been updated in many years. The U.S. industrial base producing rotary wing aircraft is currently engaged only in providing the Department with slightly evolved copies of old designs for fleet loss replacement and rehabilitation. Current capabilities are at their limit and are inadequate to address the growth of asymmetric threats. Using evolving technology to increase flexibility of vertical lift dramatically can impose cost on adversaries by forcing them to develop capabilities to defend against a much more flexible U.S. force that can operate effectively over a larger area.

A number of technologies for vertical lift aircraft have been conceived in recent years, but have been applied to upgrading only a few subsystems—and so have had limited system benefits. In the future, new vehicle development is needed change the game to ensure quick and measured response as well as to sustain operational presence and logistics support from more remote bases that are at a safe distance from adversary attack.

Operational Needs

For the last half century, land warfare waged by the Army, Marine Corps, and Special Operations Forces has taken place primarily in less developed geographic regions. Limited roads in these regions are generally poorly suited to heavy logistic throughput. Terrorists, insurgents, or state-sponsored operations, by appearing as indigenous and sometimes sympathetic populations, can disrupt these primitive ground transportation networks with proximate improvised devices or widely proliferated short-range precision guided weapons. Fixed sites, such as airports, seaports, forward operating bases, outposts, and forward area refueling points are similarly subject to both guided and unguided short range surface-to-surface missile attacks and infiltrators.

Accordingly, ground operations in forward areas are necessarily diverting combat forces to protect forward ground infrastructure and increasingly relying on helicopters for logistic support and ground force mobility. Current helicopters have consumed nearly half of the Army's fuel in some missions. Support of additional defensive combatants and forward-based helicopters is itself an added forward logistic burden.

Today's helicopters have limited capabilities: approximately 150-nautical-mile operating radius, approximately 140-knot cruising speed, and unpressurized transit at less than 15,000 feet above sea level. These short legs, slow speeds, and vulnerable altitudes limit operational flexibility and preclude the use of remote bases with their reduced forward logistic burden. The Navy also has increasing reliance on vertically capable aircraft, including anti-submarine warfare, minesweeping, transit among seagoing assets, search and rescue, and humanitarian assistance.

To alleviate these limitations, the Army has initiated an X-plane program aimed to replace the joint multirole medium vertical aircraft, with a projected initial operating capability in 2034. The program goals offer some improvements—an operating radius of 250 nautical miles (1.6 times current capability) and cruising speed of 230 knots (1.5 times current capabilities).

In late 2012, DARPA began planning a vertical lift, scaled, X-plane program examining multiple configurations with the ability to introduce game changing technology promising an notional operational radius of 500 nautical miles (3.3 times current capabilities) and cruising speeds between 300 and 350 knots (more than two times current capabilities).

This study recommends further improvements that are possible through implementation of existing technology advances. A truly game-changing system would be able to deliver 20,000 to 30,000 pounds gross weight to an operational radius of 1,000 nautical miles.

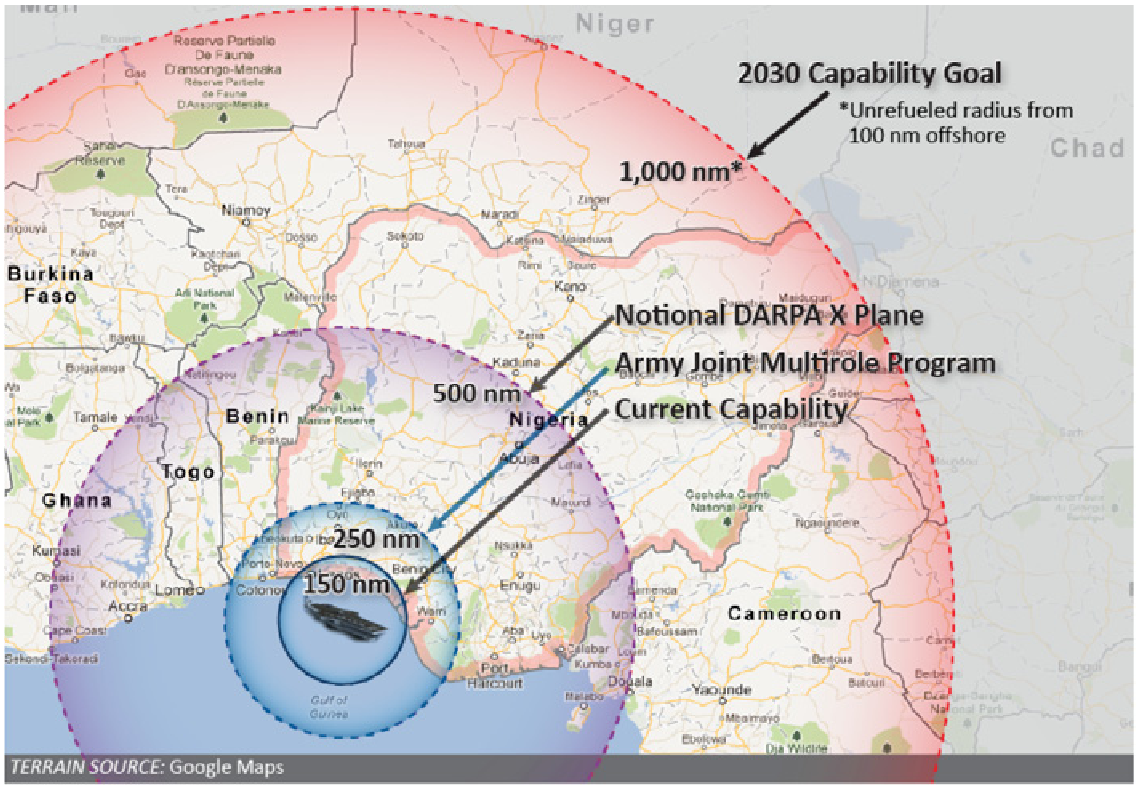


Figure 7 Radius Map with Ranges of Proposed Enhanced Vertical Lift X-Plane

Figure 7 graphically depicts the operational benefits associated with these advances on a notional country framework from a hypothetical sea base 100 nautical miles (185 kilometers) offshore.

Performance Expectations

Over the last seven years, nearly $100 million has been invested in detailed feasibility design studies for advanced vertical lift technologies. A five-fold improvement in operating radius and a nearly 2.5-fold increase in speed over current helicopter systems is within realistic reach through improvements in aerodynamic efficiency, specific fuel consumption, and empty weight fraction. Advanced configurations have achieved more than three-fold increase in the effective lift-to-drag ratio, a reduction in engine specific fuel consumption of approximately 25 percent, and a decrease of approximately 10 percent in empty weight fraction. Figure 8 shows the extreme differences in the operational radius and speed for current vertical helicopters compared to advanced vertical X-plane proposals.

The achievement of these performance improvements will enable the capability for unrefueled deep reach operating access for a radius of 1,000 nautical miles (1,850 kilometers)

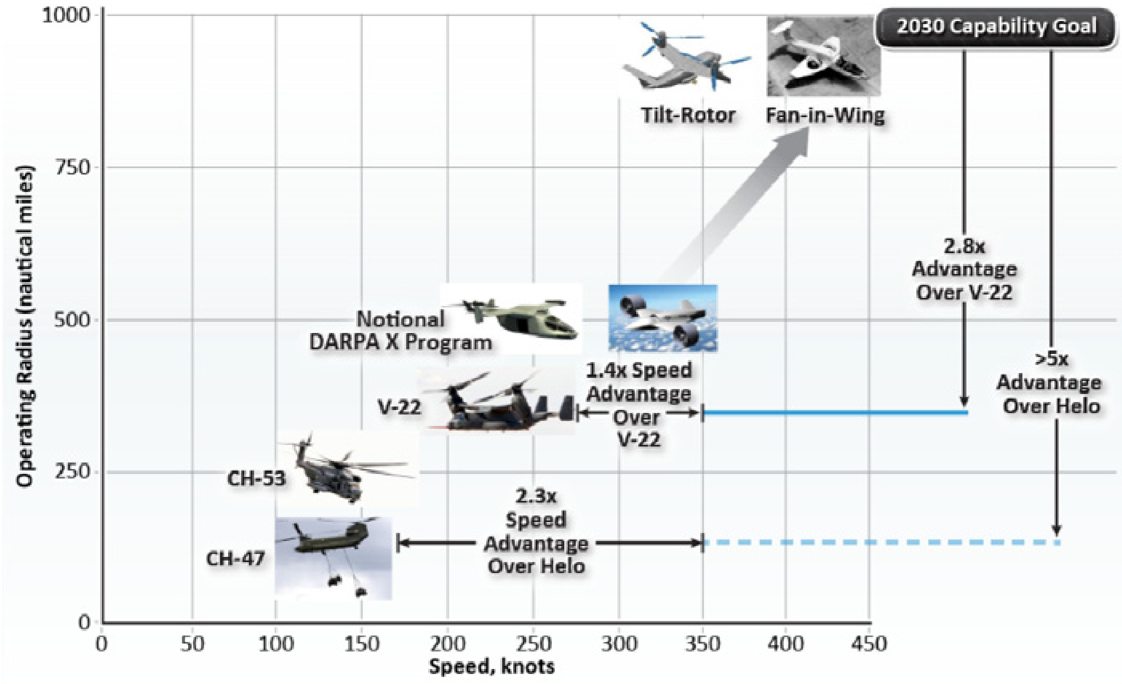


Figure 8 Operational Performance Capability for Enhanced Vertical Lift

at speeds of approximately 350 knots from edge-of-theater bases or from the sea. The operational benefits of this 2030 objective are:

- Improved range for unrefueled reach and endurance
- Use of remote bases at a safe distance from adversary attack
- Decreased forward logistic burdens
- Reduced aerial tanker dependency
- Greater operational presence and quicker response to adjacent areas

Experimentation Plan

To achieve these performance gains in an affordable manner, an initial scalable DARPA X-plane program is a prudent risk reduction approach based on projected feasible subsystems. The X-plane objectives should be three-fold: first, to ensure that the technology is scalable to achieve the 2030 objective; second, to bring more than one concept through a flight test program; and third, to achieve performance objectives that will enable the transition to a program of record before 2020. It is anticipated that a broad agency announcement will be used as the contracting authorization, and an open competition will be conducted permitting innovative concepts.

The Department has long recognized that experimentation is a necessary and viable strategy for achieving aggressive capabilities. X-plane programs are typically considered to be demonstration experiments conducted at the field level. Table 5 delineates the key elements of the vertical lift X-program within the context of the four venues of the experimental cycle.

Table 5 Experimentation to Ensure X-plane Development Success

Venues	X-Plane Program Activity
Facilitated workshops	▪ Establishes game changing requirements ▪ Conducts an industry day for tech feasibility and maturation ▪ Ensures ultimate customer involvement and concepts of operation ▪ Issues a competitive agency solicitation ▪ Identifies technology and subsystem risks
Synthetic environments	▪ Utilizes modeling and simulation to evaluate various concepts against operational scenario ▪ Utilizes modeling and simulation to validate performance metrics of speed, range, payload ▪ Assembles red team for concepts system readiness review
Facilitated small scale exercises	▪ Develops test plans for both technology and subsystem risk areas including acceptance test criteria ▪ Conducts associated tests ▪ Refines the concepts reflective of experimental results ▪ Proceeds to detail prototype design ▪ Proceeds to define the field experiment instrumentation and location
Field experiments and exercises	▪ Validates the system flight test plan and criteria for acceptance ▪ Conducts prototype flight tests on special operations ranges with U.S. Army Training and Doctrine Command participation ▪ Adapts the flight test program to reflect the test program findings

RECOMMENDATION 7

DARPA utilize its vertical lift X-plane demonstration program as a starting point for achieving advanced, scalable vertical lift that will provide dramatic improvements in operational flexibility with associated game-changing tactics.

- Ensure that the DARPA X-plane program addresses the important issues of technology, subsystem, configuration, and scalability in the requirements, thereby allowing the X-plane to have operational utility for special operations and Army missions.
- Augment the DARPA program funding by $20 million per year for 5 years to assure more than one concept reaches flight test.

4 Key Investment Opportunities to Achieve Superiority through Enhancing Force Effectiveness

Increasing the professionalism and capabilities of the all-volunteer military provides tremendous advantages. A number of innovations are discussed here that will enhance force effectiveness through improved technologies, and can also be powerful force multipliers by improving morale, enabling new tactics, or reducing training time.

Radionuclide Power to Lighten the Soldiers' Load

Electrical power sources are increasingly critical enablers of capabilities on the modern battlefield and this trend will continue unabated in the years ahead. Affordable, reliable, and secure sources of power with substantially reduced weight, space, and overall logistical demands are critically needed at several different levels.

At present, the weight of special operations' and foot soldiers' packs routinely exceeds 100 pounds, with 20 to 30 pounds or more often devoted to power packs and batteries. Additionally, because of their limited storage capacity, mission execution is dramatically hampered on a regular basis by the need to exchange or recharge these batteries. Surveillance and reconnaissance sensors and monitors are often deployed at remote, unfriendly, strategic sites with considerable effort and risk. Unfortunately, the need to periodically revisit these sites to replace power units can incur additional risk of covert detection and, even more importantly, significant additional risk to the personnel involved. Emerging power source technology, however, has the potential to improve this situation.

Power sources available and under development were reviewed for their utility for critical defense missions. Performance parameters considered include energy density, power density, reliability, lifetime, mission-scope enabled, operations, manufacturability, and cost. A wide range of technology areas were considered, beginning with advanced electrochemical batteries and hydrocarbon fuel cells, and extending to radioisotope batteries and compact fission reactors with low-enrichment fuels. The study evaluated these technologies in five mission areas of interest:

1. Extreme duration power sources for unattended, close-in surveillance sensors
2. Extended duration, portable (human-carried) power for special operations missions
3. Significantly reduced logistics footprint power for forward operating bases

4. Enhanced energy and power density sources for spacecraft
5. Enhanced energy and power density sources for unmanned undersea vehicles

Energy Options for Unattended Sensors

The most compelling mission area was determined to be extreme duration power sources for unattended sensors. Continued investment in the evolution of electrochemical batteries will clearly continue. However, current battery technologies are unlikely to meet future energy density needs for long-endurance, portable, autonomous applications. Even if projected modest increases in power densities come to fruition, the risks associated with periodic replacement of chemical batteries in hostile environments make these technologies less than desirable.

Alternatively, current technology batteries using radionuclide decay sources—similar to those found in building exit signs—provide energy densities over 100,000 times greater than the energy density of gasoline and over a million times greater than those available with electrochemical batteries, as shown in Table 6. These long-duration sources are well suited for continuous, low-power generation. In activities where higher power levels are needed only periodically, such as exfiltration of surveillance video, these could be fielded in conjunction with capacitors or ultra-capacitors.

While reasonable care must be exercised in handling radioisotope sources, the basic physics of the radionuclide material dictates that rapid or instantaneous release of stored energy is not possible. The long half-lives of radioisotopes under consideration means the rate of energy release is a constant and does not change with the material's environment. The pervasive use of radioisotopes for medical diagnostic procedures demonstrates that

Table 6 Energy Densities of Various Fuels

Energy Sources	Energy Density (kilojoules per cubic centimeter)	
Solar, Wind	NA (diffuse)	Clean and abundant, with diffuse, intermittent availability Valuable supplemental sources
Electrochemical	3–5	Primary source for personal power Development driven by commercial markets
Fossil fuels	20–35	Gasoline = 35 Primary source for vehicle propulsion and power, base power
Radioisotopes	> 100,000	Significant untapped potential
Compact fission reactor	> 10,000,000	Significant untapped potential

such materials can be safely produced and broadly distributed on a routine basis. Proper design and packaging options can safely shield soldiers and shipping personnel from radiation exposure. Similar power sources have been safely designed, manufactured, and launched for a variety of deep space missions by NASA.

The development of safe, affordable, lightweight, reliable, and very long-lived radionuclide power sources should be vigorously pursued. At present, this technology area is vastly underattended and underfunded. Only a very few efforts within the Departments of Defense or Energy research complexes are investigating the conceptual designs of radionuclide-powered batteries, and are doing so on very small budgets. This technology has great potential to have notable impact on remote sensing and Special Forces missions within the next ten years. With additional development, the possibility of large-scale deployment of safe, reliable, and effective batteries that do not need to be recharged or replaced for years at a time should be possible within the 2030 timeframe.

Micropower from Radionuclide Sources

Several design concepts are available for radioisotope powered batteries roughly the size and weight of present D-cell sized chemical batteries, but these deliver 1 to 5 watts, continuously for years. Such batteries could easily service remote sensor stations for long periods. For the Special Forces, these batteries could significantly lighten carry loads and virtually eliminate the need for recharge of warfighter on-board power for months at a time.

Two design concepts for radionuclide batteries are shown in Figure 9. One configuration, developed by researchers at the Los Alamos National Laboratory and NASA, jelly-rolls together sheets of novel advanced materials containing the radioisotopic source, customized quantum dots that capture alpha or beta decay particle energy and converts it to photons, and thin sheets of photovoltaic carbon nanotubes that convert the photons to electrical current that conducts it to the battery's terminal electrodes. Alpha particles, produced from americium or plutonium-238 emitter sources are easily captured within the thin sheets of the battery and a thin, lightweight metallic cover provides a very effective final shielding layer. Testing will be needed to verify, but it is predicted that there will be no exposure limits that would prevent warfighters from carrying these batteries for months at a time.

Researchers at the Institute for Soldier NanoTechnology at the Massachusetts Institute of Technology offer another design concept with similar performance specifications. This design, also shown in Figure 9, uses a 1 cubic centimeter mass of material infused with an alpha or beta emitting radioisotope. The thermal heat produced within the material itself is sufficient to maintain this small mass at a temperature of 1,000 Kelvins, with an outer

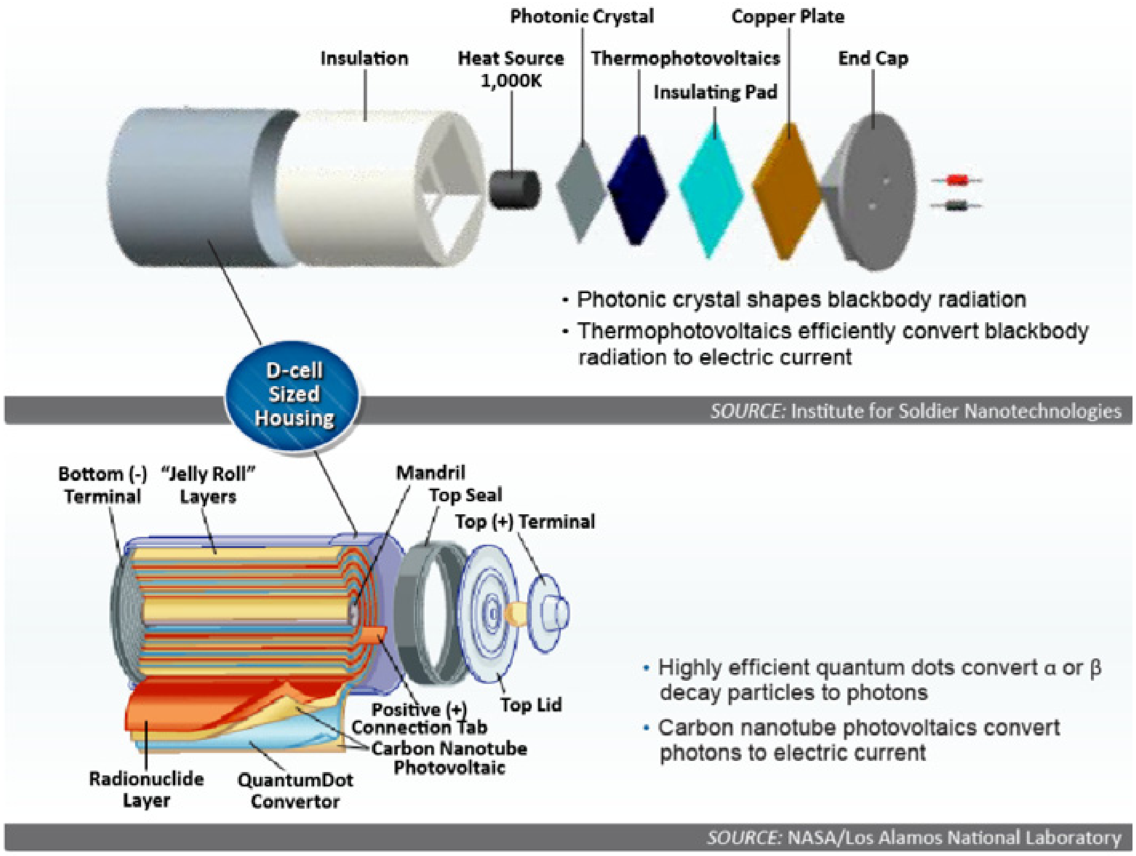


Figure 9 Radionuclide Battery Design Concepts

shell temperature of 300 Kelvins (25°C). Blackbody thermal radiation emitted at this temperature is captured using a photonic crystal, and a thermal photovoltaic cell converts the blackbody radiation to usable electric current. Size, weight, and electrical output characteristics are similar—with these batteries providing 1 to 5 watts continuous electrical output from a package weighing less than 1 pound. Early prototype designs for this concept offer conversion efficiency of more that 25 percent, but researchers are optimistic that further improvements in efficiency and overall thermal management are possible.

Much work is needed in order to realize the potential of very high energy density, radionuclide powered, and very long-lived batteries. Extensive evaluation and verification testing will need to be carried out, however, to minimize the impact of inadvertent fuel release from batteries destroyed during combat. With many years of experience in shipment and handling of radioisotopes for medical applications, no insurmountable obstacles are envisioned that would prevent the successful development and exploitation of radioisotope batteries.

Systems with Embedded Power

A 72-hour mission with today's warfighter ensemble could require over 60 pounds of batteries with the most advanced battery technology. Moreover, in addition to the weight penalty, mission impairment arises from the need to change battery packs, which is very difficult when a warfighter is underway. Although recommendations have been made for use of advanced technologies and improved operational procedures to reduce power consumption, experimentation in the field finds that there will be an ever-increasing appetite for electronic systems especially when they enhance survivability and lethality.[26] In Army war games, for example, when warfighters were presented with a higher energy density source, they opted for the same weight in batteries to increase the number of systems they could carry into battle.[27]

To simplify providing power to the warfighter's overall electronics set, both busbar and embedded power supply options should be considered. For the busbar approach, ease of integration of all on-board systems should be addressed, along with simplicity of connectivity. Alternatively, the radionuclide sources discussed above could be scaled down to very small, milliwatt level sources that could be manufactured as an embedded component within a warfighter's night vision, GPS, or other electronic packages. This would completely eliminate the need for warfighter's actions to maintain the power to these critical systems.

Finally, the operational benefits of eliminating the logistics tail associated with replaceable or rechargeable batteries cannot be overstated. This logistics tail challenge extends all the way back to the production sources. To ensure a robust supply chain, programs were established to fund domestic industrial capacity during recent conflicts in Iraq and Afghanistan for tactical batteries under the auspices of the Defense Production Act, Title III.[28,29]

Experimentation Plans

Use of nuclear material in a ground force operational environment is relatively unprecedented and would require an early examination of critical policy implications. An

26. National Academies Press, *Meeting the Energy Needs of Future Warriors* (2004), p. 65. Available at time of press at http://www.nap.edu/openbook.php?record_id=11065
27. From the capability exercises and technology wargames conducted by the Natick Soldier Research, Development, and Engineering Center.
28. Mark Buffler, *Title III of the Defense Production Act* (Presentation to NDIA Manufacturing Division, 2009). Available at time of press at http://goo.gl/hnDeJ
29. The National Academies Board on Science, Technology, and Economic Policy, *Building the U.S. Battery Industry: Progress, Challenges, and Opportunities* (2010). Agenda and presentations available at time of press at http://sites.nationalacademies.org/pga/step/pga_066853

Table 7 Advanced Power Sources Experimentation Campaign

Experimentation Form	Experiments	Experiment Type
Facilitated workshops	• Execute war game with operators to probe implications for doctrine, operations, training, materiel, logistics, personnel, and facilities (DOTMLP-F). Focus on cost benefit of battery replacement versus permanent embedded power • Red team workshop to explore adversary response	Discovery
On-line venues	• Deploy a broad cross-section of government, industry and military (current and retired) to interact in on-line sessions to gauge public and active duty perception of portable power sources	Discovery
Focused small-scale assessments	• Modeling and simulation based exercise to assess concepts of operations and operational utility in a synthetic environment. • Red team operational challenges, *e.g.*, handling, loss of devices	Hypothesis, Demonstration
Field experiments	• Demonstrate safety with surrogate or prototypes. Include operational environments stresses and projectile impacts • Execute long-term endurance, reliability test	Demonstration, Hypothesis

experimentation campaign is recommended to ascertain that the fielded capability is robustly safe, and that decommissioning is straightforward and affordable. Fortunately, fuel enrichment levels for systems under consideration are sufficiently low that proliferation of nuclear weapons grade materials is not a credible concern. However, the visceral reaction to any radiological device must be recognized and addressed. The salient point is that the experimentation campaign should explore the full spectrum of relevant technology and sociological issues.

NASA, in partnership with the national laboratories, has a small and productive, program for developing such power supplies for deep space applications. However, NASA's mission objectives, operational environments and acceptable cost levels are notably different than those of the Department of Defense. Consequently, the Department will be best served by taking the lead on driving development of these game changing power supplies.

An initial set of recommended experiments required to qualify radionuclide batteries for field deployment are enumerated in Table 7. This list is intended as a guide for future implementation.

RECOMMENDATION 8

ASD (R&E) direct DARPA to fund one or two applied research teams to develop and demonstrate safe, affordable, transportable, lightweight radioisotope batteries.

These teams should be comprised of strong industry, academic, and government collaborators. The study recommends program funding at $25 million per year for five years. DARPA should task these teams to:

- Investigate and address issues of radioisotope source availability and cost
- Work in partnership with Army and Navy stakeholders to identify initial needs for unattended sensor and Special Forces missions
- Set and achieve technical goals for safe, affordable, transportable, lightweight batteries providing 1 to 5 watts continuously for periods of 1 to 5 years
- Produce by the end of year three developmental batteries for detailed testing
- Produce by year four several dozen prototypes for field testing by the Services
- By year five, assess the feasibility and cost of broad scale deployment across the Department

In parallel with the technology development, USD (AT&L) should convene working groups addressing policy, regulatory, and related issues that may delay acceptance or deployment of successful technical solutions. The working groups and technology teams should also assess in detail critical changes to traditional life-cycle operations (*e.g.*, doctrine, operations, training, materiel, logistics, personnel, and facilities), along with issues related to production, distribution, disposal, and mission capabilities associated with broad-scale utilization of radioisotope batteries.

Warfighter Resilience and Performance

Uncertainty about which future technologies will be a constant concern to the U.S. military notwithstanding, one element of war *will* remain the same in 2030—the human element. The human element can have uniquely nonlinear effects, both positive and negative. This fact highlights a vexing paradox within the Department: warfighter resilience and performance enhancement, areas of great upside potential and certain relevance, suffer from minimal financial and programmatic support.

Warfighting has always been physically demanding and has become increasingly cognitively demanding over time. In the 21st century, data have become weapons in their own right. Data ubiquity, and the resulting advancement and forward deployment of the technology to exploit and employ them, has substantially increased the cognitive load on the warfighter and on every level of the command structure.

Recent breakthroughs in biological sciences, neuroscience, robotics, and nanotechnology have provided the ability to sense, assess, and improve performance across psychological, emotional, cognitive, and physical elements in ways not envisioned even a few years ago. This study focused on only two areas of this broad field—nutrition and supplementation, and warfighter-centered systems technology.

Nutrition and Supplementation

In spite of the new performance demands on the modern warfighter, the military has not notably attempted to exploit the best science and technology to optimize or tailor nutritional support for the warfighter for specific roles or performance requirements. Thus, a warfighter's diet, whether provided in a meal-ready-to-eat (MRE) or an on-base dining facility, mirrors the standard American diet. There is ample evidence that individual warfighters seek performance enhancement on their own via over-the-counter food supplements and drugs that not only have insufficient scientific or institutional support, but might even undermine or endanger performance and health. This situation—the lack of fact-based nutritional support to match the demanding high-level cognitive and physical performance requirements of the modern warfighter—may contribute to a force that is overburdened, stressed out, less healthy, and less effective than those in generations past as current efforts wind down. The rapid growth in understanding of the life sciences presents a timely opportunity for the Department to lead the search for science-based training and nutrition regimens that could optimize the health, performance, and resilience of the warfighter. While much of the basic research should occur in nondefense areas, the Department can benefit by taking the lead in the focused investigation and application of life sciences to improve warfighting resilience and performance.

Areas with great promise for improvement are a result of investments in nutrition and supplementation include:

- **Understanding metabolism**. Metabolism can be defined to include all chemical reactions that occur in living organisms, including digestion and the transport of substances into and between different cells. Not surprisingly, effective metabolism is

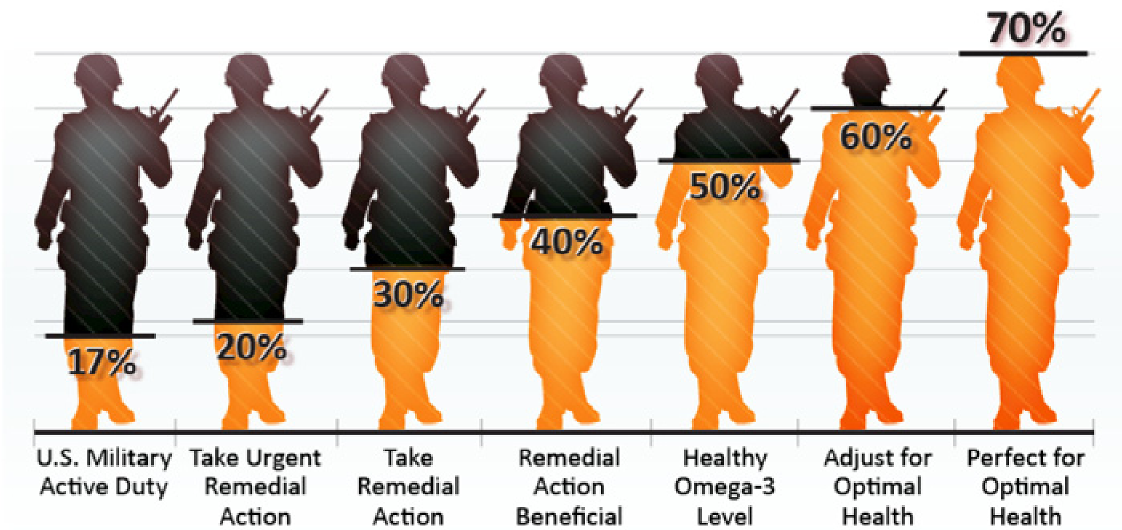
key to both physical and cognitive performance. Understanding whether warfighter metabolism might be optimized could have significant operational implications.

- **Understanding cognition, neural plasticity, and resilience**. Recent advances in neuroscience are methodically yielding a mechanistic understanding of cognition, optimal mental performance, and resilience. Coupled with advances in nutrition and the development of new neuropharmaceuticals, this understanding opens the door to the possibility of enhanced cognitive performance and resilience. Neural plasticity refers to the potential for changes in brain function and structure over time in response to environmental conditions including diet, training, and pharmaceuticals. Two such aspects that are very important to a military enterprise include protection and recovery from wounds and accidents involving the brain, and neuroplasticity-based methods to enhance cognitive effectiveness and emotional resilience.

- **Understanding the microbiome**. The enteric nervous system, a collection of neurons in the gut often called a *second brain* in the popular press, contains some 100 million neurons, more than either the spinal cord or peripheral nervous system. Approximately 90 percent of the nerve fibers in the primary visceral nerve carry information from gut to brain, not the other way around. Recent evidence supports the view that triggers and signals from the gut affect emotions, decision-making, response to stress, immune response, and learning and memory and impact cognitive performance and emotional resilience.

Although often discussed in isolation, there is a growing appreciation that cognitive and physical performances are largely inseparable. Nutritional and supplementation strategies are emerging that focus on cognitive executive function, such as enhanced vigilance. Of particular interest are investments aimed at increasing performance and resilience though defense-focused research, evaluation, and operational experimentation.

No drug discovery or development is proposed for a defense focus; rather, the Department is encouraged to explore applications for existing drugs and supplements. These efforts should focus on compounds with preliminary yet credible evidence to improve cognitive and physical performance, and that are approved by the Food and Drug Administration or have generally recognized as safe (GRAS) status. For example, restoring omega-3 fatty acids, magnesium, vitamin-D, or other nutrients to optimal levels may not only improve performance, but may restore impaired personnel to healthy and fit status, as shown in Figure 10. These and similar strategies are designed to provide the warfighter



SOURCE: B. Lands, 2011, "Prevent the Cause, Not Just the Symptoms," Protaglandins and Other Lipid Mediators, 96, pp 90-93; M.D. Lewis, J.R. Hibbeln, J.E. Johnson, Y.H. Lin, D.Y. Hyun, and J.D. Loewke, 2011, "Suicide Deaths of Active-duty US Military and Omega-3 Fatty Acid Status: A Case-Control Comparison," J Clinical Psychiatry, 72(12), pp 1585-1590.

Figure 10 Blood Level Ratios Comparing Desired (Omega-3) and Undesired (Omega-6) Fatty Acid Levels and Health Risks.

with a range of benefits to maintain peak physical and cognitive abilities both during the mission and over the long term.

Warfighter Centered Systems Technology

Much of the Department's increasing emphasis on autonomy has focused on machine sensing and algorithmic determination to replace or augment human perception and reasoning. For the foreseeable future, however, it will be absolutely essential to address how human operators are teamed with systems and to approach human-machine teaming in fundamentally new ways. It is clear, for example, that advances in the computational aspects of autonomy alone will not be sufficient to address the needs of an anti-access, area denial environment.

What is needed now is to field a more comprehensive human-machine collaboration capability system, where the physical and mental states of the operator are fed back into the weapon system, making the human a more seamless part of the overall system. This would allow adaptive automation to more effectively support individual warfighter cognitive capabilities in real-time and improve sociotechnical team performance throughout a mission. Focused technological systems can be designed to increase human effectiveness by exploiting

advances in the scientific understanding of humans coupled with advances in electronics, biotechnology, robotics, computation, and other technologies. Two critical areas are monitoring the warfighter and enhancing warfighter effectiveness.

Potential improvements can utilize technology to extend and amplify the intrinsic physical and cognitive abilities of the warfighter. Work in this area will exploit advances in robotics, materials science, actuators, control algorithms, interfaces, modeling and simulation, and machine learning. Promising technologies in this area include assistive technologies such as exoskeletons and humanoid robotic teammates, as well as a new generation of wearable sensors that are capable of continuously monitoring relevant biomarkers that measure correlates of human performance, vigilance, and resilience.

Experimentation Plans

Human performance enhancement is commonly misunderstood, perhaps partially as a consequence of the controversies surrounding violations of regulations in sport. Vaccines, caffeine, night vision goggles, and scuba tanks are just a few examples of enhancements that are widely used and accepted. Additionally, many of the most beneficial approaches to increasing cognitive and physical performance also increase resilience. Performance and resilience are increasingly understood as two sides of the same coin.

The vast majority of warfighters (over 90 percent of the Special Forces community) are now supplementing their diets without adequate guidance and assured formulation. Additionally, the unregulated and largely foreign supplement supply chain presents a notable vulnerability to attack.[30] The Department of Defense should further review this potential vulnerability and consider protecting the nutrition and supplementation supply chain with the rigor and attention brought to trusted electronic components.

RECOMMENDATION 9

ASD (R&E) oversee a comprehensive program of research, formal trials, and operational experiments to determine the value of selected nutraceuticals, pharmaceuticals, and supplementation regimes aimed at improving warfighter resilience and performance. Further, ASD (R&E) encourage the Defense Basic Science offices and DARPA to increase its research focus on human-centered technological systems aimed at leveraging and extending warfighter physical and cognitive performance.

30. MITRE Corporation, *Human Performance* (JASON Report JSR-07-625, 2008). Available at time of press at http://www.fas.org/irp/agency/dod/jason/human.pdf

- Service laboratories, perhaps in collaboration with the National Institutes of Health and other research supported by the Department, should explore N-3 fatty acids to improve resilience against major mental health impairments.
- Service laboratories in conjunction with DARPA and the National Institutes of Health should conduct research, evaluation, and operational experiments on ketone esters to determine physical and cognitive effectiveness in realistic military contexts, as well as their potential as a treatment for traumatic brain injuries.
- Service laboratories and academic partners should conduct research, evaluation, and operational experiments on a carefully selected set of nutraceuticals and pharmaceuticals in controlled laboratory and field environments.
- The Defense Basic Science offices and DARPA should be encouraged to leverage microbiome research at the National Institutes of Health to determine relevance to cognition, vigilance, and resilience. The study recommends a $30 million investment per year for five years.
- Research aimed at enabling a tighter coupling of humans and technological systems is a key component of improved warfighter performance. The study recommends a $30 million investment per year for five years.

These programs should heavily leverage the domain knowledge of the Department of Defense Human Performance Optimization Health Science Advisory Committee. In addition, meaningful incentives should be identified to encourage life scientists to participate in Department of Defense programs to improve the capability to recognize opportunities to exploit biology to create new military capability. Perhaps most importantly, while the Department embarks on this effort, it should strongly leverage the existing expertise of other government agencies, such as the National Institutes of Health, the Centers for Disease Control, and the National Science Foundation.

Historically, the U.S. military has achieved operational superiority through the early adoption of advanced technology. The Department's strong record of support and leverage of advances in the physical sciences and engineering have enabled a military capability that is global, adaptable, and without peer. The Department has not, however, had the same historical embrace in adopting the latest advances from the biomedical community. This failure to enhance the human element of war is odd given the unanimous view across the Military Services that supporting and improving the warfighter is paramount. Moreover, it is a commonplace for military commanders to assert that soldiers are the command's most valuable asset. Many of these commanders realize that the human element can have nonlinear effects, both positive and negative, on mission outcomes. The warfighter of 2030 must be able to take advantage of the advances in physiology, nutrition, neuroscience, and engineering that offer improvements to individual performance—and to the larger mission.

Next Generation Training

Training builds learned competencies to accomplish complex tasks. It runs the gamut from individual skills such as marksmanship or diagnostics to small unit operations in tank or aircraft crews to strategic skills gained through table top war games or large scale exercises. Although cognitive skills are increasingly linked to strategic goals, military operations still rely on tasks involving muscle memory, such as operating weapons. A challenge, then, is to effectively train to both cognitive and physical skills.

The development of live scenario defense training centers in the 1970s formed the backbone of the first training revolution and created a decisive edge for U.S. military forces. A second revolution to develop synthetic training environments is currently enabling another significant advance in both unit and warfighter performance. To be prepared for 2030, the Department must find new ways to learn, and must do so conscious of potential enemy capabilities. In next generation training, provisions must be made to train soldiers and units anywhere in the world, anytime.

First Training Revolution: Live Training Centers

Since the 1970s, the Military Departments have employed live scenario training to replicate the combat environment. This revolutionized training and has provided a significant competitive advantage. A striking example of the success of live scenario training is the Navy's Top Gun program, credited with increasing Navy air-to-air combat exchange ratio from 2:1 in 1969 to 12.5:1 in 1973. Air Force Red Flag, the Army National Training Center, and the Marine Corps Twenty-Nine Palms have similar success stories.

Live training involves real humans using real systems in environments and scenarios that closely approximate combat situations. Live scenario venues are arguably the best simulation of combat as they can approximate the dangerous, dirty, and difficult venues that stress human performance. Live training is without question a significant contributor to the competitive advantage demonstrated by U.S. forces over the past 40 years.

Effective live scenario training is difficult to achieve, and many costly elements must be integrated to achieve the desired output. Relevant scenarios, competent opposing forces, real time instrumentation, and integrated after-action reviews are all vitally important. The costs of personnel hours, range modernization, transportation of large forces to training sites, and throughput limit their capacity. Today, only 20 percent of force deployments can train at combat training centers.

Live training also tends to be reactive to lessons learned in the last fight. Today, excellent live training exists for the kinds of operations deployed forces have faced in Iraq

and Afghanistan, but not for the potential conflicts of 2030. Further, live training scenarios, however creative, are typically static and prescribed, and allow only a single pass through the scenario in real time. Maintaining trained opposing forces in exercises is also very costly.

Second Training Revolution: Synthetic Environments

A significant amount of Departmental effort has resulted in a robust virtual tactical training capability, especially of high-performance aviation units and fleet elements of the Navy and Air Force. Ships and aircraft equipped with sophisticated communications and recording systems readily generate data for training. Many of these systems can be linked to enable distributed training.

Training conducted on simulated equipment in a synthetic environment with a real human trainee has obvious advantages in cost, capacity, and the ability to rapidly add and expand various scenarios. The biggest limitation of this type of training today is the inability to make the human believe the environmental interaction at a level that will generate the desired competency. While significant advances are emerging rapidly in improved visual representations as well as haptic and olfactory inputs, virtual training today does not achieve the same goals as live training.

Next Generation Training: Integration

An integrated training environment combines synthetic and real world elements, with commensurate cost and capacity advantages. While use of the actual equipment can contribute to the realness of the synthetic environment, it does not automatically duplicate live scenario training. For example, although a ship's combat operations can be conducted in port using real world information, the training cannot fully simulate sea motion, environmental effects on radar and communications systems, impact of logistics, engineering casualties, and so on, which are all possibilities when actually underway.

Emerging technologies will be able to create near realistic battlefield conditions at each command echelon. Next generation training will also allow monitoring of individual performance and provide real time feedback to the individual, with the ability to replay and analyze scenarios for more in-depth feedback. The application of organic and attached reconnaissance, surveillance, and target acquisition sensor networks can also provide the same instrumentation that expensive dedicated instrumentation systems provide to installations like the National Training Center.

Extended battles in next generation training will involve every aspect of the force structure. An integrated exercise will test maintenance crews, logisticians, intelligence feeds, and other reachback support.[31] The warfighter must use what is provided in the real world, rather than a pristine machine that anyone can operate flawlessly and requires no maintenance. If a logistician delivers an *iron mountain* to the exercise, then a participant has to get it to the warfighter—whether the bullets are at the bottom of the pile or the top.

Adding a physical dimension to the synthetic training experience incurs several advantages. For example, athlete training today employs sophisticated body chemistry measurements to optimize training regimes and has developed complex feedback techniques to surmount spatial separation.

Benefits of Expanded Scenario Development

The cost and capacity of live training necessitates scripted scenarios with normally only one pass from start to finish. The scenario is only as good as the analysis of the original event; a flawed initial post mission analysis will create subsequent flawed training independent of the modeling and simulation environment that is chosen. Synthetic environments, while still susceptible to poor scenario development, support rapid exploration and discovery of different adversary actions, changes in tactics, enhanced weaponry, and so on. None of these things can be accomplished within the limitations of live training.

A game-changing advantage of more agile synthetic environments is the ability to explore scenario options in both breadth and depth. For example, training value can be hindered if the evaluation is linked to a readiness grade, and original or novel approaches may be judged ineffective because the evaluation system is biased to the scenario. The ability to engage the training with different guidelines encourages creativity and innovation. This was demonstrated by an early instrumented battle, 73 Easting, a tank battle in Desert Storm. The United States was fortunate to capture the battlefield in sufficient fidelity to replay the scenario. To take full advantage of such opportunities, the U.S. needs to improve the capture fidelity to enable replay in a synthetic environment against a more sophisticated foe, perhaps one with more capable intelligence, surveillance, or reconnaissance capabilities. A campaign of experiments can be pursued that varies

31. P.F. Gorman, *Learning to Learn: Reminiscences and Anticipation* (Paper IF1101, Conference on Interservice/Industry Training, Simulation, and Education, 2011).

scenarios, inserts new technology-enabled capabilities, and uses targeted crowd sourcing to explore and assess potential new courses of actions across cultural lines.

Great value can be extracted by coupling lower-cost synthetic environments with live field exercises. A rapidly developed, low-cost version of the synthetic environment can serve as a test bed for the research community, and can enable the incorporation of big data analytics and human terrain modeling. Especially important is the ability to use the same tools used to create scenarios to program synthetic environments, or to make smarter acquisition decisions.

Developing next generation training will not replace the live training conducted at the National Training Center and other similar live training venues. Properly designed, next generation training is designed to augment and enhance training by replicating live training capability at home units, and to provide through the use of synthetic environments the ability to train in real world operations.

Issues and Opportunities

Table 8 lists some of the different advantages and disadvantages of live and synthetic training, as described above. Leveraging the best aspects of all types of training and by refining integrated training can address several shortfalls and could significantly enhance warfighter performance.

With the proliferation of networked sensors and processing systems, many military installations today have access to operational systems that can serve the dual function of satisfying the mission that they were developed for, while serving as instrumentation systems for home-based live training. Next generation training capabilities will eventually decouple force location with the training site. The ability to generate synthetic equivalents of test ranges and offer training to multiple units at any time at any location is a potential game-changer.

The effectiveness of synthetic training environments will be constrained until realism is achieved at every level. Nondefense applications, such as game development and professional athlete training, are making major advances today in both cognitive and physical realism. Powerful integrated cyber physical systems can sense physical and mental health and provide haptic feedback in a virtual reality environment. Commercial developers are using open source software development and crowd sourcing to yield revolutionary results that can be tapped for defense applications.

Table 8 Comparison of Real and Synthetic Training Environments

	Real World Training	Synthetic Environment	*2030 Opportunity*
Current limitations	▪ Antiquated ranges with fixed locations ▪ Transportation costs ▪ Cognitive dimension not well assessed	▪ Distrust in some segments ▪ Significant costs to date	▪ Exploits advantages of real world experience and synthetic environments
Numbers trained	▪ Fewer than needed	▪ More trained, any time	▪ Significant increase in numbers trained
Scenarios	▪ Pre-defined, static ▪ Intelligent, costly adversaries	▪ Flexible, dynamic	▪ More agile exploration of expanded scenarios
Realism	▪ Can induce fatigue, fear, and stress	▪ Rarely induce true battlefield stress factors	▪ Can achieve battlefield stress factors with alternative approaches
Effectiveness	▪ Good approximation of real combat ▪ Data and analysis constrained by existing range instrumentation	▪ Easier to tailor to new training needs ▪ Any time, any place: home-based training possible ▪ Easier to implement software measurement tools	▪ Real surveillance assets can real exercise and execution data to populate reusable data sets ▪ Discover new insights through big data methods
Costs	▪ Very expensive—range modernization, opposing force personnel, transportation costs	▪ Many unknowns—replicating current field exercise, outfit home units	▪ Cost tradeoffs understood and managed—transparent options for real and synthetic training venues

Training builds upon layers of competency with each previous level required to achieve the next desired competency. Digital capture will enable rapid data analytic techniques and far more immediate feedback. For example, when pilots return from mission, their experience can be fed back into the next day's mission, leading to higher levels of competency. Digital capture of past scenarios can also be used to rejuvenate force knowledge after passage of time. To make all of this effective, improved knowledge management is needed for all task aids, field manuals, training documents, and professional books. With intelligent knowledge management, all echelons can be linked and provide appropriate levels of education—before, during, and after exercises.

It is difficult to predict how training and associated technologies will evolve over the next two decades. Individuals who are now 10 to 20 years old, whether U.S. or adversary,

are immersed in a world of rapidly evolving technology. They will be the commanders and fighters in the year 2030. This approach will intersect meaningfully with methods used to develop leaders who expect the unexpected and are accustomed to assessing and adapting. However, what this will not do is force a senior commander to take the time to participate in the training. If administrative duties or today's crisis takes precedence, then it does not matter whether the system provides realistic conditions or not.

RECOMMENDATION 10

ASD (R&E), working with the Military Departments, institute an experimental campaign using an integrated training environment.

- In the near term, replicate enhanced training capability at combat training centers at local bases and training areas by using surveillance and reconnaissance assets and sensors as instrumentation.
- In the longer term, leverage commercial technology to instrument platforms and individuals to capture real world training experiences for units and individuals.
- Create a digital library of real world exercises and operations to be used as training scenarios that is compatible with future service architectures.
- Once the process is demonstrated, Military Departments should implement procedures to adopt proven training techniques into their readiness training processes.

5 Key Investment Opportunities to Avoid Surprise

Avoiding surprise may be the most difficult task the Department undertakes, but may also be the most important. The study identified a number of areas that will aid the Department in this endeavor.

Nuclear Proliferation Prevention

The study believed that the opportunity for technological surprise is greatest for weapons of mass destruction. A specific case is described here aimed at preventing nuclear proliferation. Additional details are provided in Appendix C.

Shifting Technology Availability

Potential adversaries have been clear in their intent to employ weapons of mass destruction. The modern history of their use in warfare reveals instances of use or potential use dating back to the war of the cities in the Iran and Iraq during the 1980s, during Desert Storm in the 1990s, against the Kurds in northern Iraq in the 2000s, and in Syria in the 2010s. Several countries are in varying states of development of nuclear weapons outside of the nonproliferation treaty regime. Further, several state and nonstate actors have indicated the intent to deploy weapons of mass destruction as part of conventional military and terrorism activities. While the threat of retaliatory action deters such use, in many instances, such actions have not occurred because of the inability of these actors to access these weapons and the material to fabricate them.

This balance is threatened by changing access to the means and ability to produce chemical and biological weapons. The fabrication and operation of facilities employing these new techniques and equipment is becoming simpler, with instructions and training more generally available at universities and on the internet. The study also learned that advances in modern chemical and biology technology can make development and production of these weapons easier to accomplish. By employing techniques available in the commercial market, users may operate easily outside of the purview of state regimes that typically control military technology. These new technologies can also make development and production of chemical and biological weapons independent of the large facilities common to such activities.

An important question remains concerning the relevance of similar modern technology to nuclear weapons capability. It is hypothesized that many advanced manufacturing technologies to include additive manufacturing—also known as 3D printing—could be applied to the manufacture of components of nuclear weapons. This possibility questions whether the Cold War era facilities that are employed by several nations will be relevant in the future. Further, many late 20th century weapons designs are available, including the conventional explosive and electronics initiators.

The study considered the possibility that nuclear material could be processed by nonstate agents. It is widely held that should nuclear material be made available to a competent government or nonstate technical establishment, the greatest barrier precluding the development of nuclear weapons would have been breached.

Should such an approach materialize, the time from initiation to weapons capability would be significantly reduced from decades needed to develop knowledge and infrastructure. The latency for the development of nuclear weapons capability will approach that of biological and chemical weapons. Such capability could create a game-changing technological surprise and potential vulnerability that deserves investigation.

Impact of Advances in Technology

The absence of classic nuclear weapons signatures can significantly degrade the potential to find indicators and warnings generally associated with the development of nuclear materials production and weapons fabrication.

The materials and equipment hypothesized to be employed are generally available on commercial markets obviating the efforts of activities such the Nuclear Material Suppliers Group to provide warning and restrict access. Such future proliferators would not require the large industrial facilities with distinctive signatures subject to satellite observation. Facilities would approach the significantly smaller facilities that are assumed for the manufacture of biological weapons. The remaining element, the need for key people with requisite technology training and capabilities, is the only element common to today's nuclear development process.

Should such a threat materialize, the impact on both intelligence and military operations would be significant and potentially transformative. The feasibility of these approaches would enable a new generation of nuclear weapons production and increase the likelihood that the U.S. military would encounter these weapons on a future battlefield. The requirement that the U.S. military would need to be trained and hardened to fight on a nuclear battlefield would increase in priority. With the exception of the strategic forces, such a capability has not been maintained since the end of the Cold War.

This development would also affect the requirement to perform the elimination missions for weapons of mass destruction in contested environments. The U.S. military is prepared to perform elimination in cooperative and uncontested environments but the complex equipment and highly trained personnel required are not easily applied to contested situations.

Finally, the probability of encountering a nuclear weapon in the U.S. homeland would significantly increase with access to this technology. With nuclear capability potentially available to nation-states, terrorists, and criminals, the requirement for more intelligent border security and consequence management teams would become evident.

Approach: Big Data and Data Analytics

Largely driven by commercial applications, such as determining customer preferences and buying patterns, there is a growing field of information technology known as big data analytics. This technology acquires and analyzes data from multiple domains and sources, in multiple formats, perhaps incomplete and with no formal structure at all. While these data may come in large volumes, these processes may be useful for ingesting, storing, and manipulating both large and small physical data volumes.

Many data analysis challenges have unique and specific applicability to problems in military and intelligence affairs. In these cases, it is not practicable to address a problem by simply going directly after key facts—*i.e.,* by taking a satellite photo, tapping a phone or internet account, or tasking an agent. Instead, a broad range of data is collected from myriad sources—many openly available—and then mined to find the indirect indicators that can be analyzed to discern the targeted facts or indicators of interest. Finding weapons of mass destruction that threaten the world between today and 2030 presents just such a challenge.

The underlying technology of this approach had its origins in the commercial marketplace, and many of the specific sources and applied techniques could have many commonalities to military problems. These include analysis of education and training, travel activity, credit card activity, procurement activity, shipping activity, as well as all of the cyber communication on cell phones, e-mail, and social media that saturates the physical world. It is likely that the military applications will require addressing a wider range of data sources featuring larger amounts of unstructured data than has been historically treated in commercial applications.

As current signatures and observables for nuclear proliferation are reduced and the only signatures available are indirect, detection may best be accomplished through big data analytics. For example, the individuals who could conduct such activities would be small in number, have specific education and training backgrounds, and would exhibit

specific work activities. A precedent for this exists in the hunt during the mid-2000s for makers of improvised explosive devices in Iraq.

Implications of Big Data Applications

For any counterterrorism activity, it is fundamentally advantageous to be able to be the first to have full knowledge of a situation, to be able to analyze the full range of actions that are possible and their ramifications, and to be able to decide and rapidly inform your forces to act. The coming years will see an increasing volume of data to be considered from a wider variety of sources; large numbers of sensors will be connected and provide a detailed view of the measurable world, at the same time social networking will increasingly provide a detailed view of the world as perceived by individuals. The social networking capability will be exploited for both situational awareness of the external world, and as part of the internal decision making process.

It is expected that by 2020 there will be 50 billion interconnected devices. These devices will be used in weather, water, power, food, transportation, and healthcare infrastructures to provide situational awareness. These devices will be used to provide increased reliability in otherwise fragile systems. In addition, tracking the use of cell phones, e-mail, and credit cards will provide an unparalleled view of individual actions.

Image understanding is still immature for defense needs. Given the expected growth in imagery from government, commercial, and private sources, improved image understanding can play a vital role in gaining better situational awareness. It is likely that aspects of image understanding will be enabled by correlating image data with other data sources. For example, credit card or cell phone data can be correlated with image data to establish that an individual should be visible from image collection devices. These events can then be used to establish the reference for future comparisons. The volume of data from image sources will be large enough that processing will have to be done locally to avoid network congestion. The definition of appropriate metadata formats is in its infancy.

The broader corpus of information will also be used to cross-check information sources to identify inconsistencies in data. Most of these inconsistencies will arise from the heterogeneous nature of the data collected. While some of these inconsistencies will have been purposefully created, identifying both cases automatically will be important.

Social networking has become an important part of commercial decision-making. It provides a real time view of customer sentiment, identifies unmet needs, and provides a way of determining key thought leaders in the external space. It also provides a platform for collaborative reasoning within the enterprise, combining the data from sensors with social

data. Gathering the questions and hypotheses from the broader enterprise team leads to more successful decisions.

Much of the data in 2030 will be collected by commercial entities, utilities, or other parts of government within the U.S. or other governments outside the United States. Access to this data will provide a much more complete picture. The privacy and legal issues faced will be different and require attention relative to the commercial space.

The analysis of large data sets is particularly interesting for problems in which the actions of a small group of people are of interest. Gaining the domain expertise will require experimentation by the government in order to understand the types of data that will be most relevant and the effective algorithms to interpret the data.

The technology to interpret the data is being developed for commercial purposes today. The Department should maintain capability at the cutting edge of the commercial capabilities and augment that with special purpose capabilities for their needs.

RECOMMENDATION 11

The Department of Defense and the National Nuclear Security Agency task DARPA assess the application of modern technology to the challenges of nuclear proliferation prevention.

- Based on the findings of the initial assessment, USD (AT&L), with USD (Policy), National Nuclear Security Agency (NNSA), Department of State, and the intelligence community should develop goals and requirements for a strategic system to detect indications and warnings for the transformed production of weapons of mass destruction.
- The program should be based in the intelligence community. Members of the threat assessment team should work in concert and have reporting responsibility to their departments.
- Using the goals and requirements developed by this group, the Defense Threat Reduction Agency should lead a co-located team to carry out a compartmented prospective threat assessment. In addition to subject matter experts from all concerned government agencies, corporate experts in big data analytics with access to intelligence data bases should also be involved.
- This team should be prepared to perform its efforts at the highest levels of security. An initial goal is to employ lessons learned from the chemical and biological weapons programs and from combating improvised explosive devices in Iraq, where methods to analyze people, networks, and supply chains were used to detect anomalies.

Horizon Scanning and Hedging

The Department must execute a hedging strategy for monitoring trends in advancing technology and positioning itself to take advantage of emerging opportunities in a timely way. In carrying out this strategy, attention must be paid to the potential for new capabilities, not only for the U.S. but also for likely adversaries.

Continuous monitoring of advancing technologies should result in the identification of thresholds and meaningful shifts in cost, schedule, and performance that could be used to assess when a developing technology is ready for practical use. This knowledge would then trigger more careful tracking of advancing technologies, the second stage of an effective hedging strategy. This hedging activity will able the Department to move from hedging to active development of a technology in a timely way.

As a component of this study, a number of technologies were considered that do not meet all the criteria for immediate key investment but are important because they offer the possibility (or threat) of game-changing capabilities. In each of the following cases, it would be severely disadvantageous if a technology was successfully developed and the U.S. was unable to benefit, or even worse, an adversary was able to take first advantage, either from an offensive or defensive posture. However, in each individual case, a confident estimate of the time for development did not warrant massive, unconditional investment. In some cases, other parties are investing research at a reasonable rate to safeguard potential Department interests. However, in all cases, a breakthrough should mandate a reconsideration of funding levels. Thus, both careful monitoring as well as built in triggers to create such reconsideration are needed. These two components are the essence of a hedging strategy.

Three areas present significant potential worthy of highlighting as part of a hedging strategy by the Department: synthetic biology, quantum computing, and advanced manufacturing. All three areas share the common attribute of experiencing tremendous recent progress largely driven by entities outside the Department of Defense. Synthetic biology and quantum computing are nascent fields with maturation timeframes that may be well be beyond 2030. It is also probable that what is envisioned today will be scarcely recognizable by that time. Manufacturing, while a more mature area, is experiencing disruptive innovation in the areas of additive manufacturing and low-cost, rapid 3D prototyping—advances redefining the fundamental economics and timing of today's manufacturing process.

Advanced Manufacturing

Significant progress in manufacturing technology is expected within this decade, leading to decreased manufacturing cost, time, and limitations. Both economic and technological reasons support this prediction. The economic drivers are rooted in a rapid rise in demand for manufactured goods spurred by globalization. This rise in demand spans a wide range in product complexity and cost, from handheld consumer electronic devices to aircraft and automobiles. The response to this demand will be large capital investments in manufacturing facilities accompanied by steady improvements in productivity. The technological enablers are rooted in advances in computation, low cost sensors, and robotics. Industrial engineers and automation designers can now take advantage of capabilities that did not exist ten years ago.

One strategy to deal with the possibility of significant advances in manufacturing technology centers on reducing the acquisition cost of the weapons systems and other equipment that the Department will begin buying in the next decade. The Department has given considerable and well-justified support to new concepts in industrial productivity. No new recommendations are offered to the Department to take advantage of advances in manufacturing for cost reduction opportunities on traditional systems.

However, some new manufacturing concepts offer the potential to produce very large numbers of moderately capable systems as compared to the current expectation of producing small numbers of exquisitely capable systems. In other words, the Department should contemplate that major advances in manufacturing technology could give new meaning to the old adage "quantity has a quality all its own." In the case of anti-access and area denial this means considering alternatives to current approaches to deploy limited numbers of very capable platforms with long range, high lethality, and high survivability. Several unconventional ideas have been presented to counter area denial strategies, with the common thread of reliance on very large numbers of reasonably capable systems. For example, by taking advantage of advances in manufacturing and developments in guidance, navigation, and control, it may be possible to field a cruise missile with modest capabilities at a cost of between $100,000 and $200,000.

Additive manufacturing—commonly referred to as 3D printing—creates an object by laying down successive layers of material, as opposed to traditional subtractive machining. Some of the operational and acquisition advantages include:

- Potential to significantly shorten logistics tails by developing capabilities for forward deployed manufacturing
- Replacing parts with diminishing sources of manufacturing supply and inserting technology into aging platforms

- Rapid adaptation through decreasing production time and increasing flexibility for prototyping and deploying unique capabilities

A key feature of additive manufacturing is the ability to prototype and manufacture unique systems and parts rapidly that are difficult or impossible to manufacture using other techniques, and the ability to rapidly share designs once the initial product has been developed. Businesses rely on cycle time for competitive advantage, and additive manufacturing facilitates innovation by reducing costs for developing and experimenting with prototypes and makes quantities of one more economic. It has the potential to reduce the time required to field new capabilities and eliminate the need to store and ship inventories of spare parts.

In developing a strategy for advanced manufacturing, the Department should consider not only what capabilities are enabled but also what a potential adversary could do with this technology.

Such investigations are likely to identify thresholds and meaningful shifts in cost, schedule, and performance that could be used as measures for assessing the applicability and utility of advances in manufacturing technology. The second component of the recommended hedge strategy lies in the tracking of such progress. This tracking should take place within ASD (R&E), and, together with the metrics suggested above, should trigger the initiation of active programs if cost, schedule, and performance thresholds are met. Given the expanding cost and time to acquire complex defense systems, as well as perhaps an emerging need to field very large numbers of less complex systems, the Department must maintain cognizance of manufacturing advances and drive the implementation of these advances into its supplier base as they occur to hedge the economics and time associated today's manufacturing capabilities.

Synthetic Biology

Synthetic biology is the design and engineering of complex biological systems that perform specific functions that do not occur in nature. It brings the rigor of engineering design and reproducibility to biological processes. The biological equivalents, for example, of amplifiers, resistors, and closed-loop control systems are causing numerous communities to rethink the art-of-the-possible with respect to biology. The significant potential benefits, as well as potential threats from this area—such as designer pathogens—warrant continued monitoring.

Several recent scientific and technological advances in biological research have led to this field, including ease and speed of genetic engineering; rapid and increasingly inexpensive DNA sequencing and synthesis; and robotic technologies that perform rapid, accurate, and

high through-put molecular operations. These tools have transformed the capabilities for genome design and construction, natural product synthesis, and directed protein design.

Perhaps the most ambitious goal of synthetic biology is the construction of functional genetic circuits in cells and microorganisms. This involves the generation of a tool box of standardized genetic parts or components with known performance characteristics, from which molecular sensors, specific response modules, and product output can be assembled, regulated, and utilized as circuits.

Significant activity in synthetic biology is ongoing not only in the United States but in Europe, Israel, and Japan. China, India, Russia, and Brazil are also making major investments. For example, China plans to increase their investment in biotechnology from three percent of their gross domestic product (GDP) today to 15 percent by 2020, and tremendous government support of the industry is evident.[32] As some experts have observed, however, "China is the 800-pound gorilla, but even if we focus on the 800-pound gorilla, we can't lose focus on the 600-pound gorillas, which include Russia, Brazil, and India."[33] Recent growth in biotechnology research publications showed a 21 percent increase in China, India, and Brazil, compared with three percent increase in the United States.[34]

Potential applications of synthetic biology range widely across scientific and engineering disciplines that can improve our nation's capabilities to respond to societal challenges, in areas such as personal and public health, the economy, energy, environment, and agriculture, as well as defense. The capacity to design complex synthesis pathways into microorganisms could support reduced-cost production of pharmaceuticals, biodegradable plastics, and fuels—all with new and improved properties. Food crops could be designed with increased nutritional content and chemical or environmental resistance properties. Engineered biological tools based on modular assemblies of genes and proteins could act within the human body to detect and respond to conditions of fatigue, disease, or other physical events. Such devices might even provide for tissue repair and wound healing. In addition, it may be possible to utilize sensors for highly sensitive detection of pollutants, explosives, or biological warfare agents in a capability to degrade and destroy dangerous substances. While all of these possibilities could have significant military applications, the technologies involved also inherently have dual uses in commercial applications. Although their ethical development will require broad discussion and input, these discussions and societal concerns are unlikely to slow global development.

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32. National People's Congress, *Outline of the 12th Five-Year Plan for National Economic and Social Development* (2011). Available at time of press at http://www.npc.gov.cn/npc/dbdhhy/11_4/2011-03/16/content_1647644.htm

33. Center for Biosecurity of the University of Pittsburgh Medical Center, *The Industrialization of Biology and Its Impact on National Security* (2012), p. 10. Available at time of press at http://www.upmc-biosecurity.org/website/resources/publications/2012/pdf/2012-06-08-industrialization_bio_natl_security.pdf

34. National Science Board, *Science and Engineering Indicators 2012* (2012). Available at time of press at http://www.nsf.gov/statistics/seind12/

Given the broad potential impact on so many facets of the future, it is not possible to provide detailed examples of the many possible synthetic biology projects worthy of investment as dictated by the triggers of a hedge strategy. However, one intriguing example is genetically engineered specific antibody production triggered by infection with any known biowarfare agent.[35] The essential components of such a system would include developing and harnessing the tools of synthetic biology for generating a library of mature antibody-encoding genes on an artificial chromosome, along with regulatory circuits to sense and respond to targeted pathogens. With such a system, the threat of biological agents as weapons of terror virtually disappears, and infectious agents become a nuisance rather than a deadly specter. It is likely that this capability would also reduce the impact of naturally occurring epidemics or pandemics, as new diseases could be quelled early in their spread. It is also possible that this capability could impact the treatments of large numbers of diseases originating from infectious agents and other causes.

It is important to note that developing and achieving the technical and conceptual advances required to advance any synthetic biology capability will simultaneously advance the entire application spectrum—both for good and for evil, because it is the technology for integrated functioning of the system that is most challenging rather than the design of any specific component of the system. This fact alone dictates that these developments be carefully monitored and that hedging strategies for both opportunity and threat be in place to guide U.S. actions.

Quantum Computing

The digital computer is indispensable in virtually all U.S. defense missions. Use of digital computing assists and, in most cases, even makes feasible, national security missions expanding capability and reducing risk. Department research greatly aided the development of these assets, including more than 40 years of exponential improvement.

As a successor technology alternative to these silicon-based integrated circuits, quantum computing is generating enormous excitement with the potential to overcome impending Moore's Law expiration. The breadth of quantum computing technologies is not limited to logic devices, but includes sensing and cryptography applications. Given the large nondefense and international investment in this area, and the potential central importance to future technological systems, it is absolutely essential that the Department not be bettered in this rapidly developing field. Because much of the relevant research will be done outside the Department, monitoring progress is necessary to react when breakthroughs emerge.

35. D. Wattendorf, Defense Advanced Research Projects Agency. Presentation to the study, September 25, 2012.

By way of example, quantum computing research has illuminated many new quantum phenomena and promises a practical quantum computer that could solve problems in cryptography, physical simulation, and optimization that would be impossible with any foreseeable computer based on today's designs.

The traditional digital computer consists of circuits that accept binary inputs and compute binary outputs, often faster than a billion times a second. A theory of computing, called the Turing machine model, has described precisely how effective a digital computer is at solving a wide range of problems. The theory predicts how much better a digital computer must become to solve more comprehensive problems with greater accuracy. For example, it predicts how much faster a computer must be to make longer-term weather prediction, more accurately predict the effect of a weapon system under identified conditions, or decrypt an algorithm.

Quantum computers offer a different model of computing where certain problems regarded as unsolvable for any classical computer can be quickly solved with a quantum computer. An example is using integer factorization and discrete log problems to decrypt public key cryptosystems. The Turing model predicts that decryption would take hundreds of years employing millions of computers. A quantum computer, however, could break such a system in nearly real time. A quantum computer can also simulate quantum systems, and hence enable development of new materials that would be out of reach using all the digital computers in the world over many years.

Just as a classical computer works by clocked transformation of digital bits—for example, adding two numbers represented in binary—a quantum computer is a computing device that works by clocked transformation of quantum bits or qubits. Unlike digital bits that have two states (0 and 1), qubits have infinitely many states during a computation. More importantly, a group of entangled qubits, bearing many parallel states of a computation in superposition, can be processed in a manner that carries out a computation on all these parallel states simultaneously. This can make solving problems exponentially faster. An exponential improvement in performance opens a wide range of new problems to new solutions.

A very complete quantum theory of computation has been developed. It has a set of universal gates, analogous to those in classical digital computers that can compute any transformation of sets of qubits. A number of important quantum algorithms have also been developed. Shor's algorithm, for example, employs the quantum Fourier transform to factor numbers. Grover's algorithm would enable a quantum computer to search for an item in a set of size "n" in time proportional to the square root of n, while a classical algorithm requires time proportional to n. To put this in perspective, searching through 10^{12} items requires time proportional to 10^{12} on a classical computer, while it takes time proportional to 10^6 on a quantum computer. To further demonstrate the state of the art,

David Wineland and Serge Haroche recently received the Nobel Prize in Physics for the physics required to perform quantum computing with a few qubits.

Two fundamental problems in building a quantum computer are currently the subject of intensive research. First, qubits are fragile. Demonstrated physical qubits live only microseconds to milliseconds and then become unusable. Second, only small numbers of qubits can be produced and controlled. Researchers have discovered ways to do error correction to help improve usability times, but quantum error correction can increase the number of qubits required to perform a computation by a factor of a thousand, exacerbating the scalability problem. Researchers hope to find physical qubits that remain viable for days and can be produced in bulk—thousands and millions.

The following requirements are proposed as key indicators for the implementation of quantum computation:[36]

- A scalable physical system with well-characterized qubits
- The ability to initialize the state of the qubits
- Long decoherence times, much longer than the gate operation time
- A universal set of quantum gates
- A qubit-specific measurement capability
- The ability to interconvert stationary and flying qubits
- The ability faithfully to transmit flying qubits between specified locations

The abilities to increase the production of qubits and to build faster quantum gates are the most critical. If they were solved, building a quantum computer can be imagined. Both involve the nature of physical qubits. Qubits have been built with the following constructs:

- Superconductor-based qubits associated with the state of a Josephson junction
- Trapped ion-based qubits, where the qubit value is the state of the ion spin
- Photon based qubits, where the qubit value is the state of photons
- The quantum states of neutral atoms trapped in an optical lattice
- Semiconductor-based qubits that encode the qubit value as electron position in a quantum dot
- Nuclear spin-based qubits (*e.g.*, nuclear magnetic resonance)
- Electron spin-based qubits, which encode the qubit value as electron spin
- Topological qubits, which encode the qubit value in the shared quantum state of a collection of quasi-particles

36. D.P. DiVincenzo, *The physical implementation of quantum computation* (2008). Available at time of press at http://arxiv.org/pdf/quant-ph/0002077v3.pdf

Once physical systems evincing stable, scalable qubits that can be controlled and produce gates are found, quantum computing development is predicted within five years. Achieving these interim goals, however, may be a long way off. Current levels of research and investment in quantum computing must be maintained and progress must be monitored and tracked to ensure that the Department will be the first to employ quantum computing.

RECOMMENDATION 12

USD (AT&L) support activities that maintain continuous scanning of the technology horizon and assessment of emerging defense problems.

- Programs are needed to interact with industry and other government organizations to monitor the status and specific milestones of identified emerging technologies, with the goal to determine whether the technology is mature enough to require concerted, Defense funding.
- In parallel with the monitoring activities, the Department should also conduct conceptual application studies to explore how the technology might be exploited to create capability advantage when it matures.
- Mechanisms should be established and maintained to ensure that senior Department leadership is alerted when potential high impact technologies are identified.

Use of Experimentation to Avoid and Create Surprise

Effective experiments are an innovation-enabler and offer the opportunity to plan for potential situations and prepare for future defense programs. These procedures can improve the effectiveness of new defense systems and can create surprise, challenge our adversaries, and help anticipate how new technologies and systems concepts might be used against U.S. forces. Significantly, experimentation provides a means for technologists and operational personnel to conceive and evolve new system concepts with the doctrine to effectively implement them.

It is significant that such an approach was the core of the Defense research and development strategy in the early 1990s that sought to take advantage of the explosion in commercial information technology. At the heart of this approach was the desire to explore, discover, analyze, and understand the potential of these new technologies, and their synergy with and enablement of military capability and doctrine. Over time, experimentation in the Department has become synonymous with scripted demonstrations, testing, and training in an environment and culture that is arguably much more risk-averse

today than it was just 20 years ago. A more detailed assessment of the experimentation landscape is provided in Appendix D.

There is extensive literature on experimentation in the Department of Defense, and it is important to differentiate experiments from training or testing.[37] Experimentation can be classified in the following ways:

- **Discovery experiments** involve introducing novel systems, concepts, organizational structures, technologies, or other elements to a setting where their use can be observed and catalogued.
- **Hypothesis testing experiments** are the classic type used by scholars to advance knowledge by seeking to falsify specific hypotheses (specifically if-then statements) or discover their limiting conditions.
- **Demonstration experiments**, in which known truth is recreated, are analogous to the experiments conducted in a high school, where students follow instructions that help them prove to themselves that the laws of chemistry and physics operate as the underlying theories predict.

Given the ubiquity, knowledge, and use of rapidly advancing technologies coupled with a global ability to translate new technologies rapidly into usable systems (including advanced manufacturing), the Department of Defense cannot continue to rely on technological superiority unless it adopts innovation enablers that allow it to anticipate, assess, and gain experience with new technological capabilities before its potential adversaries. Experimentation must fit into the entire realization cycle for new military capability—it is one of the essential elements of achieving superior capability—indeed of comparable importance to areas such as basic research and emerging technology.

This report introduces a framework called infrastructure for discovery, exploration, and analysis, named IDEA, for pursuing discovery-based experiments as an innovation enabler. During the course of this study, several experimentation highlights were found within the Department. While these are not as pervasive as desired, many experiments are done well and can serve as a basis for greater use of discovery-based experimentation as an innovation enabler. The essentials of good experimentation can provide the Department a path to exploit them to achieve superior capability in 2030.

The fundamental message is that experimentation is neither a research nor an acquisition nor a doctrinal process. As Figure 11 illustrates, it is also much greater than

37. DoD Command and Control Research Program, *Code of Best Practice Experimentation* (2002). Available at time of press at http://www.dodccrp.org/files/Alberts_Experimentation.pdf

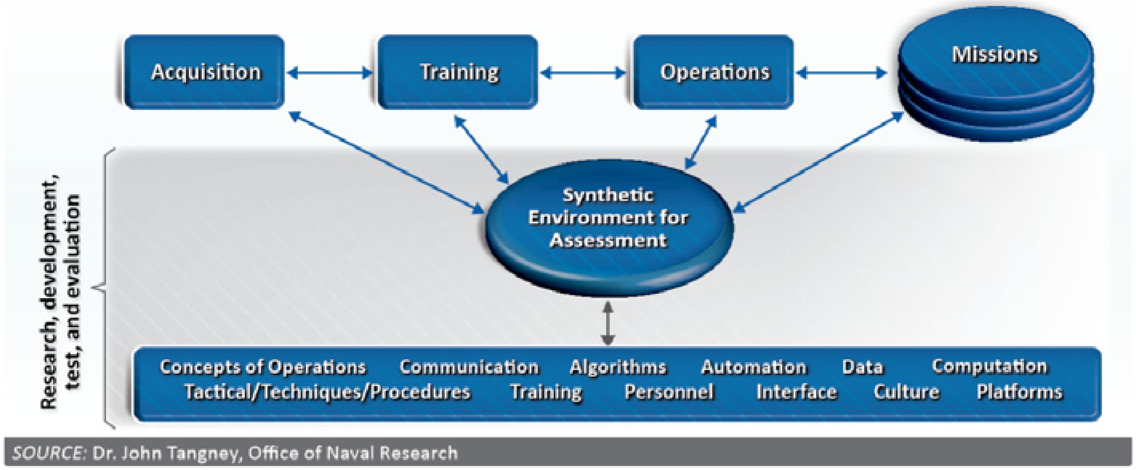

Figure 11 Experimentation Strategy versus Traditional Research, Development, Test, and Evaluation.

traditional test and evaluation. In summary, experimentation is a means to explore uncertain futures whether emanating from the emergence of disruptive technology, new capabilities using existing systems and technologies in a new way, or the evolution of security threats from anywhere across the globe.

Revitalizing Experimentation

Experimentation has long been recognized as one of the keys to innovation and transformation. Thomas Edison argued that one indicative measure of success in developing a new capability is the number of experiments that can be crowded into twenty-four hours.[38] Tom Peters, in his classic *In Search of Excellence* asserted that "the most important and visible outcropping of the action bias in the excellent companies is their willingness to try things out, to experiment."[39] Saul Kaplan, a major network editor, recently argued that "innovation is never about silver bullets. It's about experimentation and doing whatever it takes ... to deliver value."[40]

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38. Creating Minds.org. Available at time of press at http://creatingminds.org/quotes/success.htm
39. T.J. Peters and R.H. Waterman, *In Search of Excellence: Lessons from America's Best-Run Companies* (New York: Harper & Row, 1982).
40. S. Kaplan, "Business Model Innovation is All About Experimentation. It is About Combining and Recombining Capabilities from across Silos until Something Clicks" (CNN Money, 2012). Available at time of press at http://tech.fortune.cnn.com/2012/04/19/to-innovate-experiment/

The Department of Defense has long recognized experimentation as the linchpin in its strategy for transformation. In January 2012, the Department published a Chairman of the Joint Chiefs of Staff Instruction that replaced the Joint Operations Concepts Development Process with a Joint Concept Development and Experimentation Process. This instruction defines joint experimentation as the "set of analytic activities derived from unbiased trials conducted under controlled conditions within a representative environment" and reestablishes experimentation as a foundational component of the Department's efforts to address joint force capability gaps.[41]

But how should the Department conduct joint experimentation? What processes and approaches need to be implemented so that experimentation emerges as an appreciated mechanism? Is there an approach that will enable the Department of Defense to conduct better experiments than it has in the past? One such approach is captured in Figure 12.

Recognizing several key notions would enable the Department to revitalize experimentation. Fundamentally, a tailorable campaign of experimentation is needed that continuously explores the utility and implementation of new capabilities while continuing to search for other potential solutions to joint capability gaps. A cyclic process is needed in which the investigation of various capabilities and their operational utility is conducted in increasingly realistic and demanding environments until an appropriate level of confidence is achieved to deploy the capability. Cycles within cycles are needed to examine and explore

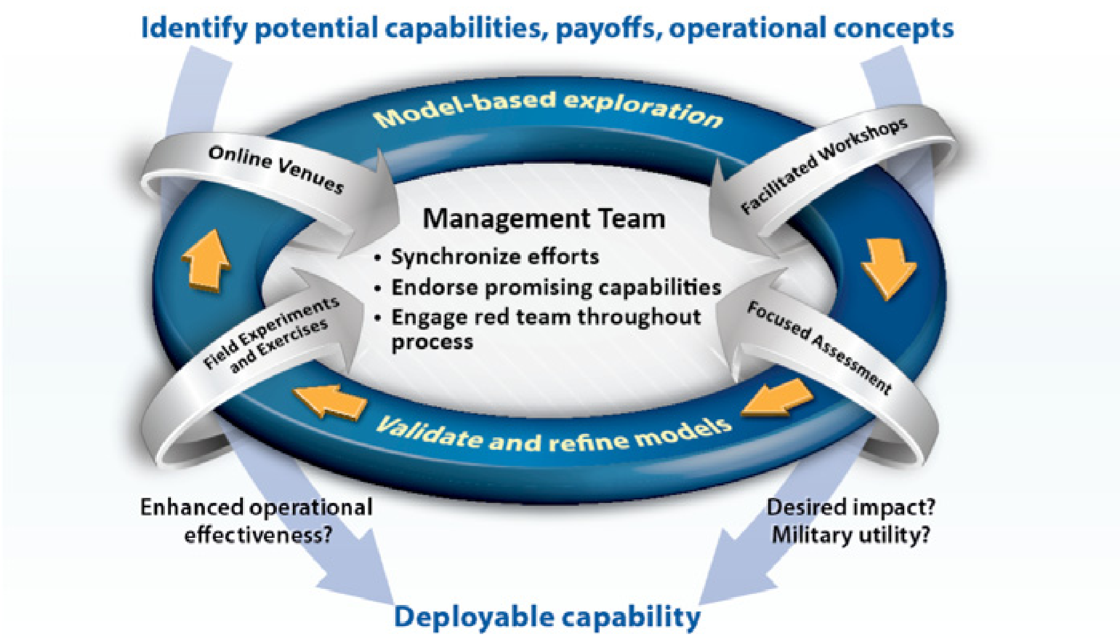

Figure 12 Experimentation Campaign Cycle

proposed capabilities multiple times within each venue until the capability is considered mature enough for the next venue within the experimentation campaign cycle.

Experimentation must be recognized as neither research nor an acquisition or doctrinal process. Rather, it enables exploration of uncertain futures where that uncertainty is driven by any set of factors, including the emergence of disruptive technology or the evolution of security threats.

Experimentation Venues

Experimentation in different venues provides different results. The following four venues are all useful, however.

1. Online venues

As the Department of Defense explores, for example, options for enhancing the resilience and performance of the individual warfighter, an approach such as crowd sourcing might expose multiple options that are already in use by the general public. Crowd sourcing is a distributed problem-solving and production model in which a problem is broadcast to an unknown group of solvers in the form of an open call for solutions. Users (the crowd), then submit solutions that are owned by the crowd-sourcer. This crowd sourcing would be conducted in a continuous fashion, providing an enduring source of diverse ideas and multiple perspectives for further experimentation. The principal benefits of this approach are three-fold:

- Enables experiments that inherently involve a large number of geographically dispersed participants
- Creates a realistic environment for studying social dynamics, political responses
- Maximizes the span of the net one can cast for new ideas and approaches

Some key characteristics of on-line venues include the ability to:

- Engage the world in the experiment
- Explore noncombatant responses to the scenario
- Open the aperture for topics not previously considered
- Discover key variables, bounds, and unknowns
- Use anonymous comments to gain diversity of thought and maximize perspectives
- Explore the value of shared situational awareness
- Assess community acceptance

2. Facilitated workshops

The exploitation of facilitated workshops can focus on examining the potential operational utility of various capabilities. These workshops should allow the experimenter to understand how a proposed capability might be integrated with other capabilities to address the identified gap. These workshops are also a venue where new concepts and new scenarios can be conceived and discovery of futures are encouraged. Such workshops should create a forum of diverse talent, bringing together warfighters, policy makers, requirements writers, threat analysts, and technologists to fully explore the opportunities provided by the proposed capabilities. These facilitated workshops would support real option analysis, allowing decision makers to decide whether to invest in, endorse, discard, or further experiment with a proposed capability. A successful workshop should introduce potential disruptive advances from outside the Department of Defense and should enable the audience to envision what might be possible.

Note the emphasis on exploration, visioning, and the employment of diverse participants from beyond the Department of Defense. Examples of facilitated workshops that have been applied in the Department include NexTech. This is a series of workshops that provide a forum for intellectual exercises where the workshop participants outline a range of potential solutions and possible framework for solving problems. They discover game-changing technologies in a notional set of scenarios, and then design a campaign.[42]

The Fursiferi Versuti workshops are a compressed format alternating between innovative paradigm shifting exercises and topic-specific idea capture. The goal is to guide critical thinking in an open, noncompetitive, vendor-agnostic arena. The participants refine questions and provide initial analyses through open source exploitation, while factoring in culture and context. Disruptive thought, unencumbered insights, and clashing perspectives are encouraged.

3. Focused small scale or simulation-enabled assessments

The conduct of these classes of experiments would enable the Department of Defense to explore the impact of the proposed capability and to confirm whether or not the capability demonstrated military utility or met particular technical performance objectives. This venue would provide the opportunity to repeatedly explore, particularly in a simulation based environment, the military utility of a capability in numerous scenarios or as a part of several unique mission capability packages. The Army's current efforts to conduct semi-annual warfighter-led experiments designed to integrate and rapidly progress the Army's tactical network could be enhanced by full scale experiments conducted in a simulation based environment that explored multiple network configurations across a spectrum of

42. Pia Wanek, Noetic Group, *NeXTech.* Presentation to the Defense Science Board, 19 July 2012.

scenarios to identify the best solutions to actually explore in the very expensive and resource-intensive live environment. Some key attributes of small-scale assessments include the ability to:

- Experiment with the systems at hand, if necessary emulate an advanced capability
- Explore *what ifs* with the virtual modeling and simulation tools
- Integrate existing and future system analysis tools
- Record everything to ultimately enable full replay with the option of changing key variables

One example of small-scale assessments within the Department of Defense is the annual TRIDENT SPECTRE exercise run by the Center for Asymmetric Warfare.[43] TRIDENT SPECTRE serves as a venue for various members of Special Forces, conventional forces, and intelligence community organizations to collaborate on and evaluate technologies and techniques related to tactical intelligence in a technical, operations, and safe environment. The exercise also provides the opportunity for capability developers, such as scientists and engineers, to interact directly with tactical operators, collectors, and analysts to improve tactical intelligence technologies and techniques that will enhance the operational capabilities of the special operations and intelligence communities.

As part of the exercise's white team, personnel from the Center for Asymmetric Warfare were responsible for evaluating the technology experiments relative to each project's stated objectives, looking at measures of effectiveness, and measures of performance, as well as against the overarching operational objectives of the event.

4. Field experiments and exercises

Finally, field experiment is the full scale deployment of the capability to ensure that the option under consideration does enhance operational effectiveness at scale. This venue is intended to explore whether or not the proposed innovative solution goes beyond merely improving the current ability to execute missions. Field experiments have a long legacy in the Department of Defense. Field exercises should not be confused with developmental or operational testing and evaluation or training. However, much of the technology and infrastructure for testing, and especially training, is especially useful for field experiments and exercises.

The Marine Corps recently deployed an experimental forward operating base to Afghanistan to assess performance in rugged operational conditions while relying solely on renewable energy sources and energy-saving techniques. The facility was established

43. S. Vogel and P. Phillips, TRIDENT SPECTRE. Presentation to the Defense Science Board, 19 July 2012.

in Helmand province. The project began with an experiment to determine baseline requirements for company-size and smaller bases that typically must provide their own fuel, electricity, water, and food. From there, the Marine Corps Warfighting Laboratory, the Combat Development Command, the acquisition community, and others evaluated existing commercial, off-the-shelf technology able to meet those needs.

The approach also includes three components that are critical to the successful execution of the experimentation campaign cycle. The first is a suite of innovative new tools adopted from across commercial industry that ultimately encourage and promote best practices and reduce the time and cost of getting to high value experimental results. Next, is a management team that is empowered to resource appropriate efforts, ensure the sharing and cross pollination of analytical results, frame the individual experiments to inform a larger but focused set of issues, set realistic expectations and manage the experimentation campaign cycle to satisfy those expectations, and, most importantly, encourage and endorse those experimental efforts that reveal what cannot work or what capabilities are inappropriate for deployment. All experimentation should retain an outward focus and this management team should ensure that other branches of the federal government, commercial technology providers, state and local government and coalition partners are engaged in the experimentation process. The final component is an active red team that challenges the construct of the experimental campaign cycle to ensure it is properly structured and resourced to address the issue at hand. The red team is also tasked with continuously identifying those simple countermeasures that can thwart the most promising capability, and ensuring that the portrayed threat in each experimental venue has the appropriate latitude and capabilities to challenge the proposed capabilities or concepts.

Implementation Planning

The Department of Defense has long recognized the need for and value of experimentation. Most senior Department leaders understand that experimentation fuels the discovery and creation of knowledge and leads to the development and improvement of products, processes, systems, and organizations. As the Department enters an era of reduced budgets, new threats, and global challenges, revitalized experimentation will be needed to provide the fuel for the transformation that the Department is pursuing.

Analytic activities are underway within USD (AT&L) to examine key current and emerging military missions in an end-to end perspective—finding vulnerabilities, opportunities, and gaps considering research, development, and acquisition. This is an excellent foundation to select experimentation campaigns. The next step is to establish a funded set of experimental campaigns on critical warfighting challenges.

The topic areas would be those deemed critical for future innovation, threats, and opportunities. Example experimental campaigns could be constructed on topic areas such as anti-access and area denial—including cyber, electronic warfare, and space warfare domains; counter weapons of mass destruction, in partnership with the Assistant Secretary of Defense for Nuclear, Biological, and Chemical Weapons; or inexpensive production of weapons, possibly including advanced manufacturing.

These campaigns should have protected funding lines, would use the full spectrum of experimentation types from facilitated brainstorming all the way to full scale field exercises, and would be visible to USD (AT&L) leadership.

Finally, these campaigns, rather than a single experiment, should be tied to major operation exercises conducted at regular periodicity by the Combatant Commands, such as Terminal Fury in the Pacific Command or Austere Challenge in the European Command.

RECOMMENDATION 13

USD (AT&L) foster a robust experimentation program that includes discovery and analysis of the potential of new technologies, rather than only demonstrating them at development milestones.

In parallel, Military Department service acquisition executives should develop processes to better share use of tools and infrastructure that exist in training and simulation-based experimentation domains.

Many of these existing tools, while developed for other purposes, such as training, can be easily leveraged for campaigns of experimentation. Those tool capabilities that do not exist should be resourced by the Military Services as they expand the use of experimentation into the structure of formal training and exercises.

It is critically important to drive effective experimentation knowledge into the culture of the Department of Defense. To do this, experimentation must become part of the existing structure of training and exercises in the Military Services—and must be integrated into training and exercising in the civilian workforce. An example of an effort that can aid in this goal is the establishment of a mentoring experimentation *boot camp* for early career officers with experimentation experts that would last one to two weeks.

An imperative to maintain military superiority over the coming decades is that the Department leadership must keep a consistent and clear emphasis on the role of experimentation in order to create and maintain a culture that learns and evolves.

APPENDIX A
Strategic Contexts and Capabilities

Strategic Contexts for Potential 2030 Scenarios

Eleven strategic contexts were identified in the study that, together, embody likely future scenarios that will require a unique capability or technology. For each strategic context, the study members identified defining characteristics; then, by looking at forecasted demographic changes, declining military resources, and the current geopolitical arena, they described the differences between the present day and 2030.

Each context included likely adversary sets and other significant areas of geopolitical change. The enduring national objectives that will lead to peace and stability in all world regions were also described. Finally, the critical capabilities that will be needed in 2030 to meet these challenges were listed for each context.

1. Homeland protection

This is the broadest of the strategic contexts. In addition to the United States being difficult to defend because of its large geographic size; free movement of its population; and open borders to trade, commerce and visitation, it also has organizational challenges relative to jurisdiction of multiple state and federal agencies to support homeland protection. Furthermore, the United States has distributed assets, most of which are in the private sector, making them more difficult to defend. Expected changes by 2030 include significant population growth and urbanization, which will result in a more vulnerable infrastructure particularly in coastal areas where urbanization is concentrated. Furthermore, there will be a greater importance on border defense by 2030.

- *Defining Characteristics:* Widely distributed assets with high percentage in private sector; difficult to defend; organizational challenges
- *What Will Be Different in 2030?* Growth in population and urbanization; greater importance on border defense; more vulnerable infrastructure
- *Enduring National Objectives:* Prevent attack against the U.S. in any domain; rapidly restore critical infrastructure; provide defense support of civil authorities

- *Critical Capabilities:* Worldwide situation awareness; inherently self-defensible systems from cyber attacks; effective defense and resilience from bio, nuclear, high energy explosive attacks

2. Peer or near-peer military competitors at the nation-state level

These competitors have the capability to defeat U.S. forces using similarly organized armed forces in areas adjacent to their homelands. Their rapid economic development allows them to invest in modern military equipment designed to defeat deployed U.S. systems. Peer-competitors are more likely to be dependent upon Middle East oil than the United States.

- *Defining Characteristics:* Capable of defeating U.S. militarily through sustained investment enabled by economic growth; existential threat
- *What Will Be Different in 2030?* Increasing challenges from those who target U.S. military capabilities to design their forces; global power projection in all domains; greater competition for the commons
- *Enduring National Objectives*: Deterrence (nuclear, conventional, cyber); freedom of the commons; selective alliances and coalitions
- *Critical Capabilities:* Deterrence of weapons of mass destruction and cyber threats; protection or alternatives to space and cyber; engagement and shaping; addressing human enhancement

3. Regional adversaries

These are also nation-states but differ from the peer-competitors due to their smaller size and mostly regional presence. Some have closed societies with large anti-access capabilities. By 2030, these adversaries could likely have a more global reach with significant capability to produce weapons of mass destruction. These states will likely seek additional increased lethal capabilities.

- *Defining Characteristics*: Nation-state; smaller scale than peer or near-peer; local presence
- *What Will Be Different in 2030?* Increased lethal capabilities; global reach; anti-access capabilities
- *Enduring National Objectives:* Selective alliances and coalitions; eliminate weapons of mass destruction; assured access

- *Critical Capabilities:* Worldwide situational awareness; deterrence of weapons of mass destruction and cyber threats; smaller lethal, survivable forces (sea, air, land); put deeply buried targets at risk

4. Security partners and alliances

These allow for sharing of mutual interests in protecting against common adversaries, the exchange of information, and the sharing of resources, including military-military exchanges and training. Given the global economic pressures, the current traditional allies however will not have the capability or the capacity by 2030 that they have had in the past. This will require the U.S. to be more effective in its management of these partnerships. These partnerships and alliances are also dynamic and depend on each situation. Partners for one situation may align with an opponent in another scenario.

- *Defining Characteristics:* Information exchange; sharing of resources; military-military exchanges and training
- *What Will Be Different in 2030?* Traditional allies have less capability and capacity; dynamic security partnerships
- *Enduring National Objectives:* Work with others to advance U.S. interests; maintain advantageous relationships; leverage partner capabilities
- *Critical Capabilities:* Compatible mission command framework; ability to share information; interoperable systems

5. Failed or failing states

These represent a scenario context in which the central government is losing or has already lost control to anarchy, warlords, or civil war. Based on information received during the course of the study, an increased number of these states are expected by 2030. Failing states are a target for internal and external influences, especially stateless terrorist organizations that can exacerbate regional and global instability or disagreements between secular and religious leaders.

- *Defining Characteristics:* Central government is losing or has lost control (anarchy, warlords, civil war)
- *What Will Be Different in 2030?* Increase in number; target for internal and external influences; exacerbate regional and global instability

- *Enduring National Objectives:* Limit negative impact of failing or failed states on U.S. interests; shape conditions to avoid failing states; prevent adversaries from taking over failed or failing states
- *Critical Capabilities:* Threats identified and tracked continuously; engagement before threat becomes significant; smaller, more lethal, survivable forces; protection against cyber and threats from weapons of mass destruction

6. Stateless threats

This is an ideology-based context that has no boundaries and very few, if any, physical assets at risk, but does have visible and tangible impact. In this context, the information domain will prove to be both an asset as well as a liability by 2030, and we will likely see a greater multidimensional lethality from these threats.

- *Defining Characteristics:* Ideologically based; no boundaries; no physical assets at risk; requires visible impact
- *What Will Be Different in 2030?* Information domain as both asset and liability; greater multidimensional lethality
- *Enduring National Objectives:* Negate their impact by eliminating their effectiveness; deny access to resources; shape perceptions
- *Critical Capabilities:* Threats identified and tracked continuously; engagement before threat becomes significant; smaller, more lethal, survivable forces; protection against cyber and threats of weapons of mass destruction

7. Transnational organized crime

This is another context beyond nation-states that is economically-driven with no physical boundaries. It also prefers anonymity. As with the stateless threat context, information will have the potential to be both an asset and a liability in this realm. What is certain is that transnational organized crime will be even more highly networked in 2030 than it is today and may be linked to stateless threats.

- *Defining Characteristics:* Economically driven; no boundaries; prefers anonymity
- *What Will Be Different in 2030?* Information domain as both asset and liability; highly networked
- *Enduring National Objectives:* Negate their impact by eliminating their effectiveness; deny access to resources; shape perceptions

- *Critical Capabilities:* Threats identified and tracked continuously; engagement before threat becomes significant; smaller, more lethal, survivable forces; protection against cyber and threats of weapons of mass destruction

8. Transnational corporations

These require their own scenario context because of their global access, focus, and research and development. While they often have global ownership and leadership, they also have the unique ability to affect national and local legislation, not necessarily following the direction of the United States. These types of corporations will be more numerous and larger in 2030 and will most likely lead to the exploitation of new technologies and advanced manufacturing capabilities. Furthermore, they will have more political influence and possibly a larger impact on the global economy. This trend may cause the U.S. to lose some of the special relationships for defense and security it has historically enjoyed with global companies with headquarters and heritage in the United States.

- *Defining Characteristics:* Global access, focus, research and development; global ownership and leadership; ability to affect local legislation; does not follow state direction
- *What Will Be Different in 2030?* More and bigger; lead exploitation of new technology; advanced manufacturing capability; politically more influential
- *Enduring National Objectives:* To retain the capability to access the technology and the capabilities of transnational corporations
- *Critical Capabilities:* Ability to capitalize on development of their technologies and capabilities; worldwide situational awareness and intelligence

9. Favorable access to the commons

This is a physical and logical strategic context that is privy to localized piracy, cyber attacks, space dependence, and sea lane access. The Arctic regions will be one area of vital importance by 2030. In addition there will be increased traffic across all the commons, and the United States could see a threat to its current dominance in this area.

- *Defining Characteristics*: Localized piracy; cyber attacks; space dependence; sea lane access
- *What Will Be Different in 2030?* Arctic region; increased traffic across all commons; threat to U.S. dominance
- *Enduring National Objectives*: Shape international standards and protocols; assure access to the global commons; provide secure international trade; assure military access

- *Critical Capabilities:* Worldwide multidomain situational awareness; ability to influence activities within commons; ability to freely operate within commons

10. Individual actors

These are individuals who form small groups that have access to cyber threats and weapons of mass destruction and do not feel bound by others' laws or ethics. Individual actors often have a rogue leader and lack any national identity. They also use technology for force multiplication. Dynamic group formation will become faster and easier by 2030, while at the same time polarization will increase. The United States will likely see sophisticated cyber attacks from this group, which will also have the ability to manufacture at an individual level. Furthering the importance of this group is that we could see them with a world-class biological threat capability available by 2030.

- *Defining Characteristics:* Small group formation; access to cyber threats and weapons of mass destruction; not bound by laws, ethics; rogue leader; use technology for force multiplication; no national identity
- *What Will Be Different in 2030?* Dynamic group formation faster and easier; polarization will increase; sophisticated cyber attacks; world-class biological capability available at individual level; ability to manufacture at individual level
- *Enduring National Objectives*: Protect the individual's rights and U.S. interests abroad; maintain separation of military and civilian authority in domestic issues; ensure lone wolf cannot carry out objectives against U.S. interests at home and abroad
- *Critical Capabilities:* Early identification and rapid assessment of risk; ability to engage civil authorities, commercial entities, academia; intelligence sharing with law enforcement, the intelligence community, private sector, allies; more robust capabilities in Special Forces

11. Humanitarian assistance and disaster relief

This area often follows a natural disaster and requires a timely response to such catastrophic events. This context also includes the need for coalition building strategy. In 2030, we will likely see an increased number of natural disasters and more visible catastrophic events. There will also be a greater impact due to coastal concentration and climate change. In addition, there will be less capacity within the Armed Forces to assist in these scenarios, while at the same time we expect to see greater expectations for response.

- *Defining Characteristics:* Natural disasters; timely response to catastrophic events; coalition building strategy
- *What Will Be Different in 2030?* Increased, more visible catastrophic events; greater impact due to coastal concentration; less capacity within armed forces; greater expectations for response
- *Enduring National Objectives:* Rapidly restore critical infrastructure; provide defense support of civil authorities; rapidly provide appropriate logistics and life support; secure coalition support and shared capabilities
- *Critical Capabilities:* Robust transportation; tailorable logistics; tailorable communications; engagement to expand trust

Desired Strategic Capabilities

The eleven potential scenarios were then mapped against defining characteristics in order to identify the capabilities that will be needed in 2030. Common domains of interest across the scenario contexts were sought. The process entailed brainstorming desired game-changing capabilities and fact-finding from experts in a number of fields, and then mapping these desired capabilities to enabling technologies. The end product is a list of nine areas, each with a number of specific capabilities and technologies needed to ensure superiority in that area in 2030.

1. Space capability

Includes the need to both defend and reconstitute capabilities and for the United States to be able to operate without space capabilities. It also requires the U.S. ability to defend against and attack from space and protect ground links.

2. Systems inherently self-defensible from cyber attack

Protection of national critical infrastructure includes a system of networks and weapons systems. Other capabilities in this domain include resilient battle management and weapons control capabilities as well as the power grid and other control systems.

3. Smaller, lethal, survivable forces for sea, air, and land

Includes the ability to significantly reduce inherent logistic burden and provide robust portable energy. In addition, the U.S. will need high energy density and high power density sources as well as just-in-time equipping, disposability, and one-time use. It also will require organic precision and timing.

4. World-wide, multidomain situational awareness

This area will need the capability to remotely identify an adversary in a crowd and the ability to target situational awareness. It will use open source and private data and needs to allow for the U.S. to rapidly decide and act on something. It also requires the ability to exploit a billion sensors.

5. Rapid adaptation and generation of asymmetric, inexpensive capabilities

Opportunities are identified in process, skill sets, and incentives as well as the architecture. This will require enabling tools and adaptive manufacturing. This is a capability available to exploitation by adversaries which will be difficult to track and the U.S. could easily fall behind. Acquisition cycles are getting longer while the commercial world accelerates.

6. Robust tracking and defense of weapons of mass destruction

Capabilities will be needed to detect, provide rapid and remote attribution, and to respond quickly.

7. Autonomous systems

Systems will need to interface with surveillance, weaponry, communications, logistics, and various levels of autonomy. Also includes vulnerabilities and the need to defend itself.

8. Human adaptability as performance enhancement

Emphasizes knowledge of what is valuable to potential adversaries and alliances, an understanding of foreign cultures, as well as an understanding of warfighters. Requires the capabilities for exoskeletons, human performance enhancement, cognitive skills, and training.

9. Advanced manufacturing

Additive manufacturing, advance robotics, developments in nanotechnology and resulting materials improvements will both improve manufacturing productivity and allow manufacturing devices and systems that cannot be manufactured today. It will eventually support manufacturing in the field that will significantly reduce logistics tails and demand for force protection.

APPENDIX B
Beyond 2030

This section showcases selected technologies that are unlikely to provide military capabilities before 2030. While they could have game-changing potential, they were not included in the recommendations because their development timelines will exceed the study's timeframe or their risk of failing is exceptionally high. They are not specifically covered in the hedging strategies even though some are related to those recommendations.

Extreme Prosthetics

Concepts and embodiments for the aided regrowth of damaged tissue are emerging today. These promise revolutionary outcomes such as the regeneration of limbs with corresponding electro-musculo-neural control interfaces. Recent advances in prosthetics have led to structurally robust and flexible wearable prostheses, and some progress has been made in electronic control of limbs and ocular implants. However, an artificial, physical interface still connects the prosthetic and the body to which it attaches or is implanted. That physical connection is a source of discomfort and can limit the potential functionality of the prosthetic. Research is underway to develop techniques to fully integrate artificial devices with human host tissue and bone, aiding in comfort and robustness, and with the potential to augment the inherent capabilities of the patient.

Bespoke Materials

A substantial expansion of research could produce meaningful payoffs in the design and fabrication of custom materials for a variety of Department of Defense applications. This type of research would be based on desired or required properties, as opposed to inherent or adaptable features of existing materials. Examples include lasing materials that can generate any wavelength, detector array materials and associated optics for sensing from ultraviolet through infrared, structurally embedded radio antennae, high-strength lightweight materials, ultra-efficient solar cells, biocompatible materials, and cost-effective nanostructures for microelectronics, to name a few.

A particular class of applications is that of materials for cloaking and deception, designed to conceal or disguise military targets from a wide array of surveillance methods. Metamaterials have been proposed to substantially change the radar cross section of

airborne vehicles by providing optically active decoy surfaces. This capability would minimize detection and add to the adversary confusion in tactical scenarios. Such materials may enable a new class of very portable and realistic projections for use on the battlefield as well as for realistic training, simulation, and wargaming. Dynamic control of such decoys could provide even more realism and enable remote personalized communication and collaboration. Time cloaking, if extended to relevant time windows, could enable completely covert communications and eavesdropping and could extend the practical bandwidth of fiber communication links substantially. Progress at this time is limited to small-scale phenomenological demonstrations, and large-scale focused efforts will be needed to bring these concepts to practical use.

Universal Energy Approach to Warfighter Systems

A substantial fraction of today's warfighter load is devoted to batteries and the electronics that require them. Approaching the warfighter with associated equipment as a system to be optimized suggests advances across multiple areas. Research on personal-scale power generation is an obvious beginning, but must also include minimized power consumption and battery loads, wireless power transmission, and overall reduction in the size and weight of all components. Although extensive research is on-going in these areas, systems-level approaches are needed to make the warfighter a net-zero consumer or positive producer of electricity while vastly reducing the power consumption of equipment required to execute missions. Breakthroughs are needed in energy harvesting, photo-thermal-mechanical-chemical energy conversion schemes, and extremely lightweight energy storage concepts. Applications outside the immediate domain of the warfighter would include increasing the lifetime of unattended ground sensors and consumer electronics that are self-powered over their useful lifetime.

Global Persistent Surveillance via Distributed Aperture Sensing

The need exists for an integrated network of space- or air-based assets with the goal to provide continuous, all-weather, high-resolution imagery of all inhabited areas on Earth. Current global surveillance is carried out using large orbiting sensor platforms, and these are limited in size by launch vehicles and limited in number by the cost of acquiring, launching, and maintaining them. This surveillance paradigm may be disrupted by deploying arrays of small sensors that collectively behave as larger high-performance imaging systems. To accomplish this, small, cost-effective payloads must be developed that can be launched and deployed as elements of a coherent system.

If they can be made cost effective, distributed aperture constellations could offer global and persistent coverage. Payloads could include down-looking image sensors operating in the visible, infrared, and microwave spectral regions to ensure coverage at any time of the day and in any weather conditions. Resolutions are available today to identify vehicles and track dismounts; this will certainly improve with appropriate effort.

Challenges to realizing such a system are both technical and programmatic. Schemes for enhancing the resolution and for cloud and foliage penetration must be developed. Structures need to be lightweight to reduce launch costs and long-lived to amortize the system cost over many years. Novel onboard embedded processing concepts and secure communications downlinks must be developed to handle the large amounts of continuously generated data.

Thought-based Machine Control

Research is in its infancy on devices and systems for facile human-machine interfaces without physical contact, either exclusively via transmitted thoughts or aided by microelectronic implants. Systems currently exist to control computer cursors and joysticks via concentrated thought. A barrier exists, however, to the complete realization of thought-controlled machines or computers and it is unclear if that barrier is technical or psychosocial.

Potential applications of successful noncontact machine control include covert communications in a tactical scenario and teleoperation of equipment. Advances will be required in understanding the mechanisms of cognitive thought, in developing minimally invasive implants (or explants) to control cognition, and in understanding the human factors surrounding acceptance and comfort of the human-machine interface. There is also the possibility that, if the mechanisms whereby thoughts can control external devices can be understood, new insights can be made on how external devices may interpret or control thoughts.

Microclimate Engineering

The ability to provide short-duration local weather manipulation in a military engagement could offer significant transient tactical advantage. Techniques could include creating rain or fog to reduce an adversary's visibility, or creating high winds or small tornadoes to inflict ground damage. Today, designer rainstorms have been claimed to be generated by a series of ionizers placed in desert locations. During the 2008 Olympics in Beijing, Chinese scientists used rocket-launched silver iodide and dry ice to flush rain

from clouds before they arrived at the event venue. Breakthroughs are needed in order to achieve the spatial and temporal control necessary for practical military operations.

Exploitation of Entanglement Physics

There is considerable ongoing research to exploit the physics of entanglement to create practical electronic, optical, and possibly physical systems whose actions are causally linked regardless of the physical separation between them. Early stage research has involved concepts and demonstrations of the generation of entangled photons, where action on one arm of an interferometric system is mirrored—with no time delay—at another location as far away as 100 kilometers. If the distance and robustness of these systems can be improved, numerous applications in ultrasecure communications could be enabled.

Portable Compact Fission to Provide Megawatt Power Levels

Power availability is an essential enabler for a variety of defense missions. As much as half a megawatt of power is required to support small combat outposts comprised of 200 to 500 warfighters, while larger forward operating bases require between 2 and 20 megawatts. Portable fission reactor concepts are being considered or developed today that are designed to operate with low-enrichment fuel to minimize proliferation concerns, similar to student training reactors that have been operating for decades at university campuses across the United States. The negative thermal coefficient in this design means that neutron moderation decreases with increasing system temperature, leading to an inherently safe design without potential for thermal runaway or meltdown. Designs are scalable and a complete system for production of electrical power in the field could be transported inside of one or two standard shipping containers.

However, significant technical challenges remain. Many issues related to safety, acceptance, security, possible fuel dispersal and decommissioning would need to be solved before such systems could be considered for practical use. These include self-stabilization during fault conditions and the potential impact and mitigation of battle field contamination due to material dispersal during a direct attack.

APPENDIX C

Emerging Threats from Weapons of Mass Destruction

Access to the appendix is via SIPRNET or equivalent classified channels. Contact the Defense Science Board office to make arrangements.

APPENDIX D
Experimentation Landscape Assessment

Elements of Successful Experimentation

A set of tools has been identified that can enable the vision for experimentation to support innovation and transformation. The tool set includes experiment design and planning, data generation, instrumentation, and analysis. When developed, these tools will:

- Enhance the design, planning and execution of the experiments within the campaign cycle
- Facilitate the creation and management of scenarios that span the range of all missions of interest and ensure the appropriate measurement space to properly evaluate the capability
- Enable the collection and management of critical data and data sets
- Support rapid analysis of the data created through the course of the experiments

While the main focus of the framework is the design and execution of discovery experiments, tools will also support the design of hypothesis experiments that will derive from the insights generated during discovery experiments. These tools, coupled with proper training and an advanced infrastructure, will promote the right mindset for experimentation and also, in time, significantly reduce the cost and time to design experiments, execute experiments, and analyze the experimental results.

Experiment Design and Planning Tool

A tool for experiment design and planning will present the user with a design template that begins with the statement of purpose, to include explicit technical, scientific, and operational objectives. It will also make explicit the experiment type: discovery, hypothesis testing, or demonstration. The target timeframe will also be established, whether near term or a far future environment. If the latter, then there will be another template to characterize the future environment.

The next element of experiment design is to identify key questions to be answered. The tool will capture the order in which these questions will be addressed. For example, in the F-117 example, there were several questions that framed the experiment plan. What radar cross section can be achieved? Can a planar aircraft actually fly? Will the

pilots be willing to fly a low radar cross-section route so that this capability will actually provide mission benefit?

The tool will next assist the user in creating a written description and will also capture plans for free play as well as elements that will be scripted. The training required must also be described. An advanced version of the tool set will enable the automatic creation of training material, enabling high value experiments to be designed with very short lead times.

Plans for red teaming, instrumentation, data collection, and analysis are also included. The tool will also use appropriate modeling and simulation to help the user apply planning factors and ensure that appropriate time is allotted for set up, rehearsal, execution, and post analysis.

These designs and plans will be living documents. As the experiment progresses, the lessons learned can modify the questions and the tool will capture the evolution of these questions. Over time, the tools will produce a library that can be used to generate meaningful scenarios and challenge problems with significant cost and time savings.

Experiment Venues

Every experimental venue must also include an infrastructure to support data collection. Today an example of the infrastructure is the Multiple Integrated Laser Engagement System (MILES), which supports capture of ground truth at some of the training ranges such as the National Training Center.

At the simplest level, the infrastructure needs to capture the location of relevant entities over time. It may provide some additional data, for instance, the status of a vehicle or health of a participant. The infrastructure will also provide the communication support for the experiment control and observation team, which is distinct from the communication system used by the participants. An infrastructure might also need to support the capture of specific physiological measurements that might be critical to understanding an experiment focused on enhancing human performance.

Data Generation Tool

One of the biggest challenges in experimentation is the creation of the data set that will drive the experiment. The tool will assist the user in designing an experiment with appropriate fidelity data to address the questions in the experimental design. This tool will also minimize the resources required to generate effective data sets. It is also very important that these tools provide the ability to rapidly modify data sets, which will support the ability to explore new variants of questions in the course of an experiment execution.

To be able to minimize effort, the intent is to maximize reuse. This will require access to data from prior missions and experiments, and specific tools to mine those data sets and map key data elements to new scenarios. In addition, the tool will be able to capture prior game experience and identify potential anomalies.

Data Collection and Management Tools

The objective for the collection and data management tools is to ensure that sufficient data are collected to create a complete understanding of all mission events associated with the experiment. The instrumentation to collect these data needs to minimize impact on the experiment participants, thereby reducing artificiality and maximizing suspension of disbelief. A particular capability that will add high value is the ability to use modeling and simulation to extract key measurements that should be tracked, and to provide visualizations that will identify key trends.

This data collection tool is envisioned to have the following components.

- The first component will collect data that is tightly integrated with the experiment design. By associating data to established plans, expected workflows, and potential behaviors, collection will support rapid analysis.
- The second component will manage the collection of the data and provide users with early, automated assessments that ensure the experiment is being carried out as planned. Automated data collection devices coupled with trained observer teams will support the rapid integration and automated curation of the data.
- The third component is characterized as curation, which is the archiving and management element.

Rapid Analysis Tools

The ultimate objective for this tool is to support the capture of positive and negative lessons learned from the experiment in a machine understandable form. The machine understandable form will allow these lessons to be fed back into future experiment designs.

A critically important capability that this tool will support is the ability to fill in the missing pieces, such as recognizing intent of experiment participants or to fill in the data-to-decision reasoning. This is very advanced functionality, and it will require some very advanced human-machine collaborative capability. The tool will be designed to maximize the use of expected outcomes to guide this process and will also allow the experiment observation teams to rapidly build out these elements.

Key to this tool is the ability to generate the analysis results rapidly, to be able to integrate insights into subsequent events in the experiment. Results must be accessible

within hours, or even sooner. Key to this rapid analysis is the fact that the experiment design will incorporate expected models of user behavior into the analysis.

One of the key analysis functionalities is the ability for an experiment team to reconstruct mission events from an experiment and then replay those events. A particular mission event could be replayed, for example, assuming a new technology is in use by either the blue force or the adversary. These tools will allow an experiment team of technologists and subject matter experts to rapidly evolve tactics and procedures over the course of an experimental campaign. Modeling will be used for deeper analysis of results, including correlating results over a campaign of experiments.

Challenges to Effective Experimentation

The concept of failure in the context of experimentation comes in two flavors. First are experiments that reveal strengths or weaknesses of a particular proposal or suggested capability. These experiments are considered to be productive even in failure. A successful experimental design should ensure failure is a possibility by thoroughly stressing the proposed solution to determine when and if it might fail to deliver the advertised expectations. Experimental results from this type of failure are tremendously useful.

The second flavor of experimental failure is not productive. This results when experiments are procedurally or conceptually flawed. In the following sections, the two ways experiments can fail nonproductively are explored.

Procedural Failure

Experiments that fail procedurally are poorly planned or are inappropriately executed. Further, if linkages among individual experiments are not well-managed, campaigns of experimentation will contribute far less to the body of knowledge than they might have.[44]

This is a dangerous trend, and may lead to a loss of confidence by senior leaders in the value of experimentation, and can limit funding when efforts do not provide the expected return on investment. More importantly, ideas and conclusions may be accepted that are not based on the appropriate examination of valid evidence or that have not been fully vetted in appropriate venues against potential threats.

A number of issues can inhibit the execution of a successful experiment. Foremost are leaders with unrealistic expectations who assume the experiment will confirm their

44. National Academies Press, *Experimentation and Rapid Prototyping in Support of Counterterrorism* (2009). Available at time of press at http://www.nap.edu/catalog.php?record_id=12612

intuitive beliefs or reinforce the value of their proposed capability. These unrealistic expectations then create tension between these same leaders who want results the day after the field trials end and the analyst who wants to ensure that the analytic products are objective, credible, and defensible.

Well-intentioned but inexperienced action officers may also develop experimentation programs that are far too aggressive and do not enable adequate time for planning, training, rehearsal, execution, and post-experiment analysis. This leads to experimental designs that include too many variables and do not have clear plans linking issues to analysis to required data. Too often, plans are rushed and the experiment is managed by a pick-up team without appropriate credentials. Appropriate scenarios provide adequate measurement space and create the opportunities for an intelligent threat to operate within realistic constraints.

Collecting valid and useful data in the human-intensive, complex environment of warfighting is often overlooked and not accounted for in the experimental design. While collection of these data is tough, analysis of these data can even be tougher. Real world data collection is further complicated when the experimental unit chafes at executing the experimental requirements; many times, the preferences of the participating unit trump experimental objectives.

Conceptual Failure

Conceptual failure results from an inability to address technologies that may radically impact the existing workflow and present the opportunity for surprise by adversaries. Those with radical impacts are called formative technologies, and those that reflect that way things have usually been done are called normative technologies. Different approaches are needed to experiment in each regime.

Normative technologies are those that fit within the existing way of doing things; the technology is a better way of accomplishing a well-understood goal within the general socio-technical organization (*e.g.*, a faster horse). Formative technologies, on the other hand, are radical innovations that may enable novel goals or alternative mechanisms to reach an existing goal, but in doing so will impact the existing social-technical organization. Formative describes a dynamically forming workflow that occurs a new technology presents new uses and more changes. For example, replacing a horse with a car goes beyond substituting a horse with a faster horse; the introduction of cars impacts logistics, acquisition, and maintenance costs, changes existing tactics and procedures, and may require specialists or additional training—but also offers unanticipated opportunities beyond what a horse could do.

Formative technologies require experimentation of ideas about the technology rather than demonstrations of performance or reliability testing. When done well, this type of experimentation requires innovative experimental design, data collection, and analysis, and offers the benefits of reduced capability surprise, identification of hidden acquisition costs, concurrent evolution of tactics and procedures, and a head start on training.

While formative technologies may be adopted to meet a need, they can also originate independently of a perceived need and be thrust upon an organization. A key indicator is not the sophistication of the technology but in the impact on the workflow. Examples of formative, game-changing technologies are the internet, smart phones, or unmanned systems. These formative technologies may be low cost and readily accessible by both allies and adversaries, thus experimentation should explore both the opportunities and limitations to achieving mission effects.

A standard, current approach to experimentation is to focus on the technology within a normative context as the prime unit of measure. This can quickly devolve into testing driven by the repeatability of the technical performance metric. Such experiments rely on scenarios where mission effects and the workflow are scripted based on current practices, and preclude exploration of new missions enabled by the technology.

Experimentation with formative technologies focuses on the human-machine collaboration as the prime unit of measure through exploration of missions and workflows. The end result is knowledge of how the technology contributed to the data-to-decision process. It is not a demonstration because experimentation requires engagement by the stakeholders—vendors, warfighters, red teams, and so on—to actively probe for implicit assumptions, unintended consequences, and undesirable follow-on effects. Experimentation with formative technologies is not testing because defining acceptable performance is premature without the context of a mission and workflow.

Experimentation with formative technologies requires new guidelines for designing experiments, new methods of data collection, and new metrics, measures, and methods for analyzing the data. Guidelines for designing concept experimentation should be established for specifying the fidelity and scale needed to provide sufficient realism. Data collection will have to move from observable electro-mechanical performance data (*e.g.*, The tank went so far, so fast.) to metadata about the larger systems (*e.g.*, Is the right data reaching the right person at the right time? Does the warfighter trust the data?).

New quantitative and autonomous mechanisms are also needed to replace the manpower-intensive, and sometimes disruptive, methods currently used to measure whether the decision or action resulted from a useful technology-mission-workflow combination or the ability of a particularly talented individual to work around the constraints of the technology to accomplish the intent. New metrics and analysis methods

are needed because the experiments are not reproducible and big data mining techniques and machine learning may not be sufficient or applicable. Metrics are needed to explore the trade spaces of fitness, plans, impact, perspectives, and responsibility.

Experimentation with formative technologies has many benefits. It can reduce capability surprise, as it encourages the blue forces to understand how to exploit a new technology and how an adversary might use it. An exploration of the impact on the workflow and trade spaces can proactively identify hidden acquisition costs such as manpower skill sets and expensive life cycles. Concept experimentation indirectly offers the concurrent evolution of tactics and procedures which can be further refined and also form training objectives. Similarly, the problems and bottlenecks encountered by participants suggest key points that must be clarified during training.

Case Studies in Successful Defense Experimentation

There have been multiple efforts across the Department of Defense since World War II where the principles of experimentation exposited in this report have been successfully applied to innovate and rapidly deploy technologically superior capabilities for U.S. forces. Case studies are presented that span the space described by experimentation versus traditional research, development, test, and evaluation.

F-117 Aircraft

The F-117 is a well-known aircraft that was rapidly developed to exploit innovations in stealth technology.[45] The program is notable because of the use of experimentation principles to develop this system in record time. The F-117 emerged from a program named *Experimental Survivable Testbed Program* later to become *Have Blue.* The need for such an aircraft emerged after the conflicts in the early 1970s demonstrated the capabilities of Soviet-built air defense systems. DARPA initiated studies, which continued through the summer of 1975, to determine if an aircraft could be built that could defeat these air defense systems through greatly reduced radar cross-sections. By 1979, the *Have Blue* program had demonstrated the low radar cross-section design.

The heart of experimentation in rapid innovative programs is to explore, discover, analyze, and understand the potential of these new technologies and their synergy with and enablement of military capability and doctrine. The *Have Blue* program and its successor

45. Federation of American Scientists, *F-117A Nighthawk*. Available at time of press at http://www.fas.org/programs/ssp/man/uswpns/air/attack/f117a.html

development program, *Senior Trend,* exhibited a number of important characteristics that can guide program development today.[46]

- Include operational communities in the selection and management of prototype projects. This ensures that such prototyping efforts are meaningful and not just *hobby shop* projects.
- Rather than avoiding risk altogether, structure acquisitions programs to accommodate risk by minimizing the costs of failure. Attempting to eliminate too much risk too soon will often stifle innovation.
- Use experimentation to identify when technology development will enable manufacturing breakthroughs. Advances in radar cross section prediction techniques helped designers to understand how to design low observable aircraft. Successful realization of this breakthrough relied heavily on experimental measurement.

Some of the key lessons learned from this program begin with taking risks and failing smartly to encourage innovation. Another key concept is to use experimental, empirical measurements to validate concepts, and most importantly, to demonstrate the technology and the concepts of operation before crafting requirements.

In summary, the principles of good experimentation are rooted in lessons learned from programs such as the F-117.

Navy Aegis Ballistic Missile Defense Sidecar

In the mid-2000s, the Aegis weapon system improved its ability to do experimentation with new AN/SPY-1 radar waveforms and target identification techniques by including an on-line sidecar processor. The sidecar tapped radar data from the AN/SPY-1 ballistic missile defense signal processor and tested the data on-line, separate from the in-line weapon system processing. This approach allowed new techniques to be fully tested before moving them into the in-line processor path.

The Aegis AN/SPY-1 sidecar has been used to develop new high range resolution waveforms and discrimination algorithms for ballistic missile defense. In almost all cases, the on-line testing of new waveforms and algorithms led to the identification of processing shortfalls that needed additional engineering work. After a few cycles of experimentation and adaptation, the techniques were usually ready for operational use. The sidecar approach led to the development and transition of advanced processing techniques in a relatively short timeframe. Development work similar to the past efforts with high range resolution waveforms continue in the current Aegis AN/SPY-1 radars.

46. D.C. Aronstein and A.C. Piccirillo, *Have Blue and the F-117A: Evolution of the Stealth Fighter* (American Institute of Aeronautics and Astronautics, 1997).

Naval Special Warfare Group TRIDENT SPECTRE

The U.S. Navy special warfare group conducts an annual exercise called TRIDENT SPECTRE.[47] In 2004, TRIDENT SPECTRE was conceived as a venue to bring together experts from the development and operational worlds to innovate rapidly in an experimental setting that advances the set of tools and operational tactics, techniques, and procedures available to the deployed forces. Over a period of two to three weeks, the exercise follows a repetitive pattern of applying and modifying to maximize the contribution of the technology. Operators, vendors, and intelligence analysts come together in a way that exercises the end-to-end process of an operational scenario. The environment is designed to be collaborative with the intention of enabling vendor-to-vendor learning through activities designed to stress the operating envelop of tools to the point of failure. The result has been rapid iteration of development cycles that yield capability improvements that may have not otherwise been identified. The high stress environment, driven by the operational tempo and the peer-to-peer performance pressure, is designed to force developers to collaborate outside their technical domain through interactions with both other developers and operators. Operators played a significant role by relating directly how they use the tools and brainstorming *what if* enhancements that are then made in real time and incorporated into the next day's spiral. Multiple levels of learning occur concurrently in this exercise:

- Tools are exercised and innovated in ways that the developers would not have conceived in their laboratories.
- Tactics, techniques, and procedures are enhanced using updated tools and new data products that may now be available.
- Activity-based intelligence was formed by applying analytical techniques against collected data to identify already observed indicators that were not known at the time they were collected. These techniques allow previous data points to be mined and used to fill in key intelligence gaps.

NeXTech Workshops

NeXTech workshops identify and assess the implications of emerging technologies in future warfare. Because the military culture has promoted linear thinking, there has been a tendency to underestimate the pace and potential of technologies. This form of experimentation helps to connect disparate disciplines, expertise, and viewpoints, thereby gaining insight into the "integration" factors across multiple technologies and concepts of operation. The primary objectives of this form of intellectual experimentation:

47 S. Vogel and P. Phillips, TRIDENT SPECTRE. Presentation to the Defense Science Board, 19 July 2012.

- Identify the consequences of potentially game-changing technology areas from technical, social, political, legal and ethical perspectives, and educate options
- Foster much needed discourse on these issues by convening nontraditional stakeholders in an unconventional setting
- Develop a basis for forming recommendations for how to plan and invest in science and technology in an era of prolonged resource constraints
- Introduce talented junior and mid-grade military officers to a forum for creative and critical thinking on the future strategic environment while providing a model for rigorously testing the potential military and nonmilitary effects of new technologies prior to significant investment by the U.S. government

Fursiferi Versuti

Fursiferi Versuti are facilitated workshops that emphasize the crafting of innovative solutions to a focused problem through the convergence of people with seemingly unrelated backgrounds and world views. Participants are guided through a series of frame-shifting exercises that bring the world of nonkinetic activities (*e.g.*, law enforcement, finances, criminal justice) to national security challenges. These workshops provide for a safe environment in which to embrace disruptive thought and clash of perspectives. Highlighted attributes:

- Compressed, rapid, two-day format in nonattribution environment
- Group composition carefully designed to bring nontraditional skills, backgrounds and perspectives
- Experimental in feel, collaborative in style
- Solutions are strategy-informed, but tactical-centric
- Collection of ideas are preserved and documented for new applications

Marine Corps Warfighting Lab Concept-based Experimentation

The Marine Corps Warfighting Lab conducts concept-based experimentation. The Marine Corps uses this form of experimentation to define and articulate what the Marine Corps of the future should look like in combat development terms, considering doctrine, operations, training, materiel, logistics, personnel, and facilities. This experimentation approach supports both long-range development of warfighting concepts, and shorter range evaluation of potential technology game changers. It seeks to develop and evaluate new operational concepts and their associated tactics, techniques, procedures and

technologies, and use those results to inform combat development, as well as to identify the next technological tipping point.

Inherent in this approach is the desire to bring together scientists, technologists, and experienced warfighters so as to innovate through analysis and synthesis of relevant scenarios through the eyes of multiple perspectives. Various methods and tools are used throughout these exercises to ensure a healthy learning environment:

- Live forces
- Technology forecasting and assessment
- War gaming
- Modeling and simulation
- Continuous analysis of threats and opportunities

Capability Exercise and Technology War Games

The capability exercises and technology war games conducted by the Natick Soldier Research, Development, and Engineering Center is an experimentation approach tailored to the unique challenges of the warfighter system. Natick is unique in their approach to technology war games. Salient characteristics of the technology war games include:

- Brings together scientists and experienced warfighters
- A disciplined approach to explore warfighting problems and conceptual solutions
- Innovation through analysis and synthesis of relevant scenarios informed by multiple perspectives

Most significant contribution of the technology war games is that it challenges the participants—seasoned operators, technologists, and red team—to reconsider exquisitely documented historical scenarios with the availability of new technologies. A particular example executed in 2010 was to ask the operators to reconsider an Afghan operation with a new portable power source—a battery with a two-fold increase in energy density. Many critical and surprising insights can be gleaned from this experiment that could not have been gained from a straightforward analysis.

Commercial Best Practices in Experimentation

The study was cognizant of commercial practices in experimentation. These formal techniques and best practices from the commercial domain could better inform practices within the Department of Defense and vice versa. There are several trends in experimental methods and statistical inference that have been applied in the Department

of Defense—for example, in operations research—but have been far more broadly deployed in commercial organizations. For example, formal techniques for design of experiments are now being applied across all functions of the commercial enterprise.

Commercial companies utilize experimentation and consider it to be an integral and natural part of their processes. This is driven by the intense competition and overall pace of change. Competition includes all elements of features or capabilities at specific price points and the marketplace demands innovative new products on a regular basis. Companies that succeed in this environment implement best practices throughout all of their business processes including research, concept development, design, production, sales, and support.

Design of experiments is one such best practice that allows an accelerated rate of learning that, in turn, can lead to innovative and competitive products that in turn achieve market success. A strategically planned and executed experiment may provide a great deal of information about the effect on a response variable due to one or more factors. Many experiments involve holding certain factors constant and altering the levels of another variable. This one-factor-at-a-time approach to process knowledge is inefficient as compared to current statistical approaches to experimental design.

Best practice techniques for design of experiments are supported by a wealth of knowledge and by methodologies that have been developed and documented over many decades.[48,49,50] A robust experimentation program can effectively be used to evaluate alternative approaches that are embedded in all business processes.

Design of experiments is a proven best practice tool but significant efforts are required to achieve its potential. Successful companies begin by adopting one of the many proven methodologies for design of experiments, and then promoting the concept that design of experiments applies to all phases of the product cycle. This is followed by an education campaign for the managers and all those involved to understand how design of experiments can improve their chance of success. Finally, upper management must demand that design of experiments be used daily in the decision process of all business areas.

Design of experiments is currently used around the globe to enhance performance of commercial enterprises. It is a best practice and is supported by a wealth of information, methodologies, and educational material. Broad adoption of this best practice could benefit the Department of Defense in many areas.

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48. G. Taguchi, *The System of Experimental Design: Engineering Methods to Optimize Quality and Minimize Costs* (1987).
49. P. Goos and B. Jones, *Optimal Design of Experiments: A Case Study Approach* (Wiley, 2011).
50. K. Hinkelmann and O. Kempthorne, Des*ign and Analysis of Experiments, Volume I: Introduction to Experimental Design* and *Volume 2: Advanced Experimental Design* (Wiley, 2008).

Acronyms and Abbreviations

3D	three-dimensional
ASD (R&E)	Assistant Secretary of Defense for Research and Engineering
CSAC	Chip Scale Atomic Clock
C-SCAN	Chip-Scale Combinatorial Atomic Navigator
C2BMC	command, control, battle management, and communications
DARPA	Defense Advanced Research Projects Agency
DOTMLP-F	doctrine, operations, training, materiel, logistics, personnel, and facilities
GDP	gross domestic product
GRAS	generally recognized as safe
HiDRA	High Dynamic Range Atomic
IDEA	infrastructure for discovery, exploration, and analysis
IMPACT	Integrated Micro Primary Atomic Clock program
JDAM	Joint Direct Attack Munition
MILES	Multiple Integrated Laser Engagement System
MRE	meal-ready-to-eat
NASA	National Aeronautics and Space Administration
NNSA	National Nuclear Security Agency
PINS	Precision Inertial Navigation System
PNT	positioning, navigation, and timing
R&D	research and development
SCADA	supervisory control and data acquisition
UASC2	unmanned aerial system command and control
U.S.	United States
USD (AT&L)	Under Secretary of Defense for Acquisition, Technology, and Logistics
USD (Policy)	Under Secretary of Defense for Policy
WGS	wideband global satellite

Terms of Reference

THE UNDER SECRETARY OF DEFENSE
3010 DEFENSE PENTAGON
WASHINGTON, DC 20301-3010

ACQUISITION,
TECHNOLOGY
AND LOGISTICS

MAR 15 2012

MEMORANDUM FOR CHAIRMAN, DEFENSE SCIENCE BOARD

SUBJECT: Terms of Reference – Defense Science Board Study on Technology and Innovation Enablers for Superiority in 2030

The 2012 Defense Strategic Guidance includes the tenet that technological superiority will continue to be a critical enabler for superior U.S. warfighting capabilities. Along with technologies developed in the private sector, the research and development investments that the Department of Defense (DoD) will make over the next several years will become the basis for future capabilities provided by new and enhanced systems and operational concepts. However, declining budgets will force the Department to be selective in its research and development investments.

The Defense Science Board (DSB) is requested to conduct a study of emerging technologies that will enable the next generation of dominant military capabilities to be in development or fielded by 2030. The products of the study should be:

1. A set of recommendations intended to guide the DoD research and development investments in applied technology and technology demonstrations over the period of 2014 to 2020;
2. Mapping of the identified technologies to applications and capabilities that may be enabled; and
3. For a select set of promising technologies, recommended experiments or concept demonstrations that foster innovation and provide entry ramps to enhance operational capabilities via block upgrades to existing systems or as entry ramps to new systems and operational concepts.

The study should be guided by the January 201 2 military strategy guidance titled "Sustaining US Global Leadership: Priorities for 21st Century Defense."

The study should include surveying and assessing the potential for significant advances in technology outside DoD that could contribute to future military capabilities. These advances could augment DoD investments in areas such as: quantum computing, micro-electronics, robotics, nanomaterials, genetics, "big data," alternative energy sources, advanced materials, and modeling and simulation.

Technologies that have the potential to significantly enhance or transform the nature of warfare in the air, sea, land, space, and cyber regimes should be the focus of this study.

A study subcommittee will be authorized access to programs at all classification levels.

TERMS OF REFERENCE

I will sponsor the study. Dr. Jim Tegnelia and Mr. Jim Shields will serve as co-chairmen of the Task Force. Dr. Melissa Flagg and Lt Col Dan Tadevich, U.S. Air Force, Office of the Assistant Secretary of Defense for Research and Engineering, will serve as Executive Secretaries, and CDR Doug Reinbold, U.S. Navy, will serve as the DSB Secretariat Representative

The study will operate in accordance with the provisions ofP.L. 92-463, the "Federal Advisory Committee Act," and DoD Directive 5105.4, "DoD Federal Advisory Committee Management Program." It is not anticipated that this study will need to go into any "particular matters" within the meaning of title 18, U.S.C., section 208, nor will it cause any member to be placed in the position of action as a procurement official.

Frank Kendall
Acting

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Dr. James Tegnelia	University of New Mexico

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Dr. Stephen Cross	Georgia Institute of Technology
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Mr. Ted Stump	Strategic Analysis, Inc.

Briefings to the Study

May 22, 2012

Dr. John Battilega	Private Consultant	A Core Chinese Military Technology Investment
Hon. Frank Kendall	Under Secretary of Defense for Acquisition, Logistics, and Technology	Discussion
Hon. Zach Lemnios	Office of the Assistant Secretary of Defense for Research and Engineering	Discussion
Dr. Martin Libicki	RAND Corporation	Global Demographic Change
Mr. Andrew May	Defense Office of Net Assessment	Discussion
Dr. Michael Pillsbury	Private Consultant	Thoughts on China

June 19–21, 2012

Dr. Stephen Bachowski	National Air & Space Intelligence Center	Human Performance Perspectives Outside of the U.S.
GEN James Cartwright	U.S. Marine Corps, Ret.	Innovation
Mr. Dan DeMots	Defense Office of Net Assessment	Discussion
Dr. Eric Eisenstadt	Private Consultant	Genomics and the Warfighter
Dr. Ted Gold	Institute for Defense Analyses	Lessons from IDA Joint Advanced Warfighting Program
Mrs. Robin Hicks	Office of the Assistant Secretary of Defense for Research and Engineering	Current JCTD Program
Dr. Jack Jackson	Institute for Defense Analyses	Lessons from IDA Joint Advanced Warfighting Program
Mr. Joel Resnick	Institute for Defense Analyses	Lessons from the IDA Joint Advanced Warfighting Program
Mr. Ben Riley	Office of the Assistant Secretary of Defense for Research and Engineering	ACTD Trends, Changes and Operational Perspectives
Mr. Will Roper	Office of the Assistant Secretary of Defense for Research and Engineering	Strategic Capabilities Office
CAPT Dylan Schmorrow	Office of the Assistant Secretary of Defense for Research and Engineering	Optimizing and Enhancing Human Performance- Fantasy and Fact
Dr. Robin Staffin	Office of the Assistant Secretary of Defense for Research and Engineering	Defense Basic Research
Dr. Kevin Woods	Institute for Defense Analyses	Lessons from IDA Joint Advanced Warfighting Program

July 19–20, 2012

COL Kevin Felix	U.S. Army Capabilities Integration Center	TRADOC
GEN Paul Gorman	U.S. Army, Ret.	History of Experimentation
Dr. Mike Macedonia	Science Applications International Corporation	Virtual Worlds & Experimentation
Dr. Fenner Milton	U.S. Army Night Vision and Electronic Sensors Directorate	Trends in EOIR Sensors
Dr. Paul Muessig	U.S. Marine Corps Warfighting Laboratory	Marine Corps Experimentation: Priorities and Challenges
CAPT Peter Phillips	U.S. Special Operations Command	TRIDENT SPECTRE
COL Paul Roege	U.S. Army Operational Energy Office	Nuclear Energy Role in a Secure Energy Portfolio
Dr. Adam Russell	Intelligence Advanced Research Projects Activity	Human Performance Modification
Mr. Al Shaffer	Office of the Assistant Secretary of Defense for Research and Engineering	DoD S&T Roadmaps and End States
Dr. Erik Syvrud	Defense Advanced Research Projects Agency	SOCOM Experimentation (TNT)
Mr. Setev Vogel	U.S. Special Operations Command	TRIDENT SPECTRE
Ms. Pia Wanek	Noetic Group	NeXTech Game Overview

August 20–24, 2012

Dr. Albert-László Barabási	Northeastern University and Harvard University	Big Data: From Network Science to Human Dynamics
Dr. Joseph Bielitzki	Private Consultant	Human Performance Enhancement and Optimization
Dr. Vincent Chan	Massachusetts Institute of Technology	Quantum Communications
Dr. Howie Choset	Carnegie Mellon University	2030 Dominance for Manufacturing
Mr. Tom Dee	Defense Joint Rapid Acquisition Cell	Joint Rapid Acquisition Cell
Dr. Oliver L. de Weck	Massachusetts Institute of Technology	Manufacturing Technology
Dr. Drew Endy	Stanford University	Synthetic Biology

Dr. G. Andrew Erickson	Los Alamos National Laboratory	Compact Power Sources; End-to-End Nuclear Threats
Dr. Marshall Greenspan	Northrop Grumman Corporation	DRFM Technology and Future Radar Sensor Systems
Dr. Gerald Manke	Naval Surface Warfare Center	Ultra-Short Pulse Laser Technology and Applications Development
Dr. Jack Obusek	Natick Soldier Research, Development and Engineering Center	Soldier RDE
Dr. Stephen Smith	Draper Laboratory	Quantum Sensing
Dr. Vladan Vuletic	Massachusetts Institute of Technology	Quantum Technologies
Dr. George Whitesides	Harvard University	New Technologies - For What?

September 25, 2012

Mr. Rob Beutel	U.S. Transportation Command	Cyber Discussion
Dr. William Coblenz	Defense Advanced Research Projects Agency	Perspectives on Digital Direct Manufacturing
BG Randy Dragon	U.S. Army Brigade Modernization Command	Enabling the Warfighter through Integration
Dr. Sean M. Kirkpatrick	Office of the Assistant Secretary of Defense for Research and Engineering	Future Trends in of U.S. National Security Space Architecture
Ms. Annabelle Lee	Electric Power Research Institute	Cyber Discussion
Dr. Erik Prentice	Office of the Director of National Intelligence	Biological Warfare
Lt Col Dan Wattendorf	Defense Advanced Research Projects Agency	Biosensing (and Responding)

October 18, 2012

GEN Keith Alexander	U.S. Cyber Command	Cyber Security
Mr. John Betz	MITRE Corporation	Analysis of GPS Alternatives

November 6, 2012

Ms. Jessica Clay	Defense Counterproliferation Office	Chemical Weapons R&D
Dr. Robert Cohn	Office of the Assistant Secretary of Defense for Nuclear, Chemical, and Biological Programs	Chemical Weapons R&D
Dr. Joseph Corriveau	U.S. Army Edgewood Chemical and Biological Center	Chemical Weapons R&D
Dr. John Graham	U.S. Army Medical Research Institute for Chemical Defense	Chemical Weapons R&D
Mr. Phil Lemire	National Geospatial Intelligence Center	Chemical Weapons R&D
Dr. Eric Moore	Defense Threat Reduction Agency	Chemical Weapons R&D
COL Bruce Schoneboom	U.S. Army Medical Research Institute for Chemical Defense	Chemical Weapons R&D
Mr. Gregg Walker	Defense Threat Reduction Agency	Chemical Weapons R&D

November 15–16, 2012

Dr. Reggie Brothers	Office of the Assistant Secretary of Defense for Research and Engineering	Assured Communications
Mr. Ned A. Chase	U.S. Army Research, Development and Engineering Command	Vertical Lift Experimental Aircraft
Mr. Jaymie Durnan	Office of the Assistant Secretary of Defense for Research and Engineering	Discussion
Col Tom French	Defense Space Protection Program	Space Protection Program
Mr. Rob Gold	Office of the Secretary of Defense	Assured Communications
CAPT Joe Hibbeln	National Institutes of Health	Modern Fats in Military Diets and Impaired Military Minds
Mr. Brian Holloway	Defense Advanced Research Projects Agency	Discussion
Dr. Jimmy Kenyon	Office of the Assistant Secretary of Defense for Research and Engineering	Vertical Lift Experimental Aircraft
Dr. Michael Obal	University of Southern California	Reenergizing U.S. Space Nuclear Power Generation
Dr. Carey Schwartz	Office of Naval Research	Data-to-Decisions S&T Priority Initiative

Mr. Matt Seaford	Office of the Assistant Secretary of Defense for Manufacturing and Industrial Base Policy	Li Ion Battery for Military Applications
Dr. Brian Shaw	National Intelligence University	Training of intelligence officers
Mr. Richard H. Simmons	Naval Metrology and Oceanography Command	Overview of Operational AUV and UUV Capabilities
Dr. John Stubstad	Office of the Assistant Secretary of Defense for Research and Engineering	Space and Sensor Systems
Dr. John Tangney	Office of Naval Research	Human Systems – Training and Interface
CDR Rob Witzleb	Office of the Chief of Naval Operations	Naval Technical Reconnaissance
Dr. Stuart Wolf	Office of the Assistant Secretary of Defense for Research and Engineering	Quantum Computing & Quantum Information Science: DOD Research and Assessment

December 5, 2012

Mr. Yosry Barsoum	MITRE Corporation	Mission Assurance

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